THE SPECIALISTS SERIES

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ELECTRIC LIGHT CABLES

AND THE

DISTRIBUTION OF ELECTRICITY.

THE SPECIALISTS' SERIES.

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AND THE

DISTRIBUTION OF ELECTRICITY.

BY

STUART A. RUSSELL,

Associate Member of the Institution of Civil Engineers.
Member of the Institution of Electrical Engineers.

WITH 110 *ILLUSTRATIONS.*

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PREFACE.

In the early days of electric lighting, the distribution of the current did not present any very serious difficulties, since the lamps supplied by each dynamo machine were generally at no great distance from it; and it is therefore only recently, since the extension of central station lighting has forced them to the front, that the problems connected with the economical distribution of electricity have, as a general rule, attracted their fair share of attention. Although a considerable amount of experience has now been gained from the results of work already carried out, much still remains to be learnt, more especially concerning the durability of the materials employed to insulate the conductors; and it has been the author's aim, in preparing this work, to present to the reader such a description of the various systems of distribution and types of cable now in use, as will, he hopes, help forward the work that still remains to be done to perfect this branch of the business of supply.

For much of the descriptive matter, the author is indebted to the courtesy of the managers and engineers of various electrical companies, both at home and abroad, who have kindly supplied him with information concerning their work; and to them he is glad of this opportunity of tendering his cordial thanks.

November, 1891.

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ELECTRIC LIGHT CABLES

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CHAPTER I.

The Electric Circuit.—Conductors and Insulators.—Early Experiments in Electrical Transmission.—Ronalds' Underground Line.—First Telegraph Lines.—Lead-covered Wires.—Gutta Percha and India-rubber Insulation.—Overhead Lines.—Early Forms of Insulators.

ALTHOUGH electricity was being distributed from several central stations before the passing of the Electric Lighting Act of 1888, and the problems connected with its economical generation and distribution had already attracted a considerable amount of attention, it was not until after that time that electrical engineers had much opportunity of studying the practical side of these problems with the aid of data obtained from actual working concerns. In the earlier days their efforts were chiefly directed to improving the efficiency of the engines and dynamos and the internal arrangements of the generating station, and the distributing apparatus received far less than its proper share of attention.

Now, however, with the large areas that are supplied

with current from central stations, the first cost of the distributing apparatus forms such a large item in the capital expenditure, and the cost of upkeep and of energy wasted in distribution has assumed such importance that this part of the system can no longer be relegated to a second place; and it is necessary, if the best results are to be obtained, to study carefully all the problems connected with the designing and installing of the cables and other apparatus that form the distributing plant.

The electric current is transmitted from one place to another by means of conductors, which must form a complete closed circuit; one portion of this circuit being in the generator, and another in the receiver, whilst the remainder forms a connecting link between the first and second. This last-mentioned portion of the conducting circuit is the distributing apparatus, and it should provide a path along which it is easy for the electricity to travel from the generator to the receiver and back again; and further, it should be so arranged that it is the only path along which the current can travel, or at any rate that no appreciable quantity of current can escape and complete its circuit back to the generator by a short cut without first passing through that part of the circuit which forms the receiving apparatus. Where several paths are available, the current will divide itself amongst them in inverse proportion to the resistances opposed to its passage, and it is therefore of the utmost importance that the resistance of the conducting circuit proper shall be very small compared with that of any other path by which the current can get back to the generator.

All known materials are to a greater or less degree conductors of electricity, and none are such perfect

conductors as to oppose no resistance to the current; yet, fortunately for the electrical engineer, there is a very marked difference in this respect between two classes of materials; one set offering a very small resistance as compared with the other, so small, indeed, that the name of conductor is applied only to materials of this class, whilst those of the second class, which offer a high resistance, are called insulators. By a suitable combination of conducting and insulating materials an electric circuit can be arranged so as to fulfil the conditions already named, one being just as necessary as the other, as without the conductor there could be no current of electricity, and without the insulator there would be no control over the path which this current should take. We see, therefore, that the problems of distribution may be divided into those connected with the conductor, and those connected with the methods of insulating it; and to these two sub-divisions may be added a third, in which the methods of fixing the insulated conductors and protecting them from mechanical injury must be considered.

For many years before the use of electricity as an agent for the production of light or motive power had become a commercial possibility, the electric circuit had claimed the attention of those engineers who were devoting themselves to the perfection of systems of telegraphy; and although the requirements of a telegraphic circuit differ in many important details from those of a lighting or power circuit, the work done by these pioneers of the electrical industry deserves careful attention; more especially since amongst the methods proposed and tried by them will be found some, which are almost identical with those in use by the electric-light engineer of the present day.

The earliest record of any attempt to transmit electricity to a distance dates back as far as 1727, when a Charterhouse pensioner, named Grey, erected a wire about 700 feet long, insulated by being suspended by silk threads, and observed the effect produced at one end of this wire when the other end was charged by applying to it an electrically excited glass rod. Twenty years later, Watson communicated shocks from a Leyden jar through an overhead line about two miles in length, the wire being supported on insulators of baked wood screwed to wooden poles, a method of insulating an overhead wire which was again tried in the early days of practical telegraphy.

The first instance of the use of a continuously insulated conductor was in 1812, when Baron Schilling successfully carried out the experiment of exploding an electrical mine, the current for which was conveyed to it by a conductor insulated with india-rubber and laid across the river Neva. Some four or five years later, Mr. Ronalds (afterwards Sir Francis Ronalds) carried out a series of experiments on a system of telegraphy at Hammersmith; when, in addition to a considerable length of overhead wire insulated by being suspended by silk threads from wooden frames, he also included in his circuit a length of rather more than 500 feet of underground wire. This wire was bare, and was threaded through thick glass tubes, the several lengths of which were butted together so as to nearly touch one another, and their ends enclosed in glass sleeves, which were slipped over the joints in the tube and fixed in place by means of a small quantity of soft wax. The glass tubes were laid in a wooden trough about two inches square, coated inside and outside with pitch, and filled up solid with the same material after the tubes were

in place. In a pamphlet entitled, "Description of an Electric Telegraph," and published in 1823, Mr. Ronalds described these experiments and the system of underground lines which he proposed to use, and on the advantages of which as compared with overhead lines he laid great stress, owing to their being less exposed to accidental damage; and it is interesting to see how completely at this early date he had elaborated an underground system, and had foreseen the necessity of making provision for easy access to the line for testing and localizing faults, by dividing it into sections with test boxes placed at regular intervals, and by providing stations at which linesmen were placed, whose duty it was to look after the different sections of the line, and localize and repair any faults which might occur.

From the commencement, in 1837, of the era of practical electric telegraphy, inventors were very busy with the electric circuit, and in the forty years or so during which telegraphy was the only commercial application of electricity, innumerable patents were taken out for improvements in conducting circuits and the methods of insulating them. Iron wires coated with copper were proposed for the purpose of combining mechanical strength and electrical conductivity, as also were copper wires with silver cores and other compound wires in order to improve the conductivity; and the stranding of wires was introduced when considerable sectional area and flexibility were required. Many patents were issued for insulators of various shapes and materials, and for methods of suspending overhead wires, amongst these latter being one granted to Wheatstone in 1860 for supporting overhead cables in towns by links suspended from wires strained above them. In the matter of insulating

materials for making a continuous covering for the conductor, the Patent Record for this period shows that proposals were made at one time or another for the use of nearly every conceivable mixture of gums, resins, waxes and bituminous compounds, with one another and also with such substances as paper, fibrous materials, spun glass, powdered glass, sand, gypsum, etc., etc., and for enclosing these cables in lead tubes. Patents were also granted for insulating bare wires underground by threading them through glass or porcelain beads, by supporting them on insulators fixed in glazed earthenware troughs, and by laying them in troughs, fitted with glass or wooden distance pieces and filled in solid with asphalte, pitch, or cement.

Some of the proposals made during this period have been proved to be worthless; but others, although not successful when first tried, have formed the groundwork on which have been built up many of the systems now in use; the difference between success and failure being due to improvements in manufacture and greater care in handling and laying the conductors underground.

In the first patent taken out by Cooke and Wheatstone, in 1837, a plan for laying underground wires was described; and in the same year a five-wire line was laid between Euston Square and Camden Town, in which the wires were covered with cotton and steeped in a resinous compound, and were then laid in grooves cut in the top and sides of Λ-shaped baulks of timber which were laid in a trench in the ground. When the wires were in position, slips of wood were placed in the grooves to keep them in place, and the whole was covered with pitch before the trench was filled in. The insulation of these wires soon failed,

and in the following year, when a line was laid from Paddington to Slough, the baulks of timber were discarded and wires insulated in a similar manner were laid in iron pipes. This line had the same fate as its predecessor, and was replaced by one overhead; but the idea of using underground lines was not abandoned, and many experiments were made with cotton-covered wires saturated with resinous and tarry compounds, and laid in metal troughs or pipes, or in wooden troughs filled with asphalte, pitch, or similar material.

None of these lines lasted long, as the insulation was not damp proof, and the resinous compounds became decomposed; but in 1845 a great step was made in the right direction by the proposal to enclose the cotton-covered wires in lead tubes,—a proposal made first by Wheatstone and Cooke, who in May of that year took out a patent of which the following is a brief extract:—Separate copper wires are wrapped with worsted thread and varnished with shellac, and a number of these covered wires are then made into a bundle with whitelead and starch, and enclosed in a lead tube. The lead tube may be made of sheet lead wrapped round the wires and soldered along the joint, or it may be moulded round the wires by hydraulic pressure in the well-known manner of making lead tubes from semi-molten metal.

In August of the same year, Young and McNair took out a patent for lead-covered wires, their method being to cover the conductor with thread and coat it with asphalte, pitch, wax, and resin. The covered conductor was drawn through a vessel containing the hot compound, then through a nozzle which removed the superfluous compound, and through a tube which passed through the cylinder containing the lead, and abutted

against a die through which the lead, at a temperature of from 250° to 400° Fahr., was forced by means of a hydraulic press. A third method was patented by Mapple, in 1846, in which the conductor was covered with cotton, soaked in tar or pitch, and passed into a lead pipe which was afterwards drawn down by being passed through rollers, or through a die, until it embraced the covered wire tightly. These three patents, dating back over fifty years, practically cover the whole ground so far as the lead casing is concerned, and describe in some detail the most approved methods which are in use at the present day; and the comparative want of success that attended the use of lead-covered wires in early telegraphic days must therefore be ascribed to the use of imperfect machinery, and to the incomplete expulsion of the moisture from the cotton covering, and subsequent impregnation of the latter with unsuitable compounds.

The first lead-covered wires appear to have been laid by the Electric Telegraph Company, in 1846, from the Strand to Nine Elms; the underground line consisting of a 3-inch cast-iron socket pipe containing two lead tubes covered with tarred yarn, in each of which there were four wires wrapped with two layers of cotton and filled in with a mixture of tar, resin and grease. The lead-covered cable was laid in lengths of about fifty yards; a sleeve of lead was slipped over the end of one length, the four conductors were then jointed, and the lead sleeve pulled down so as to cover the joint and soldered at each end to the two lengths of lead tubing. Other lines of a similar kind were laid, in which the wires were covered with cotton and drawn into a lead tube, in which there were slits made every six yards to facilitate the impregnation of the cotton covering. The

lead-covered wire was put into a cauldron containing a mixture of hot pitch, resin, and beeswax, and after remaining long enough for the mixture to get into the cotton covering, it was withdrawn, and the slits in the lead tube closed by soldering.

Cables covered with lead gave much better results than those which had previously been tried, but still their life was short, and whenever it was possible overhead lines were used in preference. About this time, however, a new insulating material was found in gutta percha; Faraday and Werner Siemens being credited with the discovery that it was a good dielectric; and in 1849 the first wires insulated with gutta percha were laid in London in cast-iron pipes. The wire was placed between two heated strips of gutta percha, which were made to adhere to it and to one another by the pressure of a pair of rollers between which they were passed. Wires covered in this way did not give satisfactory results, as the longitudinal joints between the two strips of gutta percha opened up and left the wire uninsulated; and it was not until a method was introduced by means of which the gutta percha was put on as a solid covering under pressure, that any measure of success attended the Telegraph Companies in their efforts to maintain an underground system. Even then failures were very numerous, and large sums of money were lost which had been spent on gutta-percha wires, and on laying them in conduits of iron pipe either solid or split, or of iron or wooden troughing, or of earthenware pipes.

India-rubber was also tried as an insulator, but with the methods of covering the wire which were then practised, it did not form a waterproof coating, and it decomposed too readily, so that its use never became very extensive; in fact, for telegraph work it may be

said that it was only used for indoor or overhead leading-in wires, for which purposes gutta percha was found altogether unsuitable. Although so many of these earlier lines failed and were replaced by overhead wires, there were some situations in which underground lines were a necessity; and engineers continued therefore to lay them, using for the most part gutta-percha wires, and getting better and better results as the manufacture was improved, and greater knowledge was obtained of the conditions under which the material would give the best account of itself. At the same time experience showed that the cast-iron socket pipe, with surface boxes placed at intervals of from 50 to 100 yards, was the best conduit; as it thoroughly protected the wires from mechanical injury, and allowed them to be drawn out and replaced when necessary. This form of conduit is now almost universally used for telegraph lines in England, and into it are drawn cables consisting of a number of wires insulated with gutta percha and protected by tarred tapes.

With regard to the overhead pole lines there is not much to be said, as after a short trial of insulators made of baked wood, every one settled down to the use of glass or glazed stoneware, and these are the materials most in use at the present time. The improvements that have been made in the shape and arrangement of the insulators, however, are considerable, as may be seen from the accompanying sketches of some of the shapes first employed.

Figure 1 shows the insulator used by Cooke, which was shaped somewhat like an egg with a hole through it from end to end, through which the wire passed, and which therefore afforded ample opportunities for surface leakage. The hour glass shape (Fig. 2) introduced by C. V. Walker reduced the leakage considerably, as the

wire was only in contact with the insulator at the centre, and there was therefore a greater length of surface over which the leakage current had to pass. Figure 3 shows the Bright cone, which, with modifications in the shape of the bell, is the form now generally

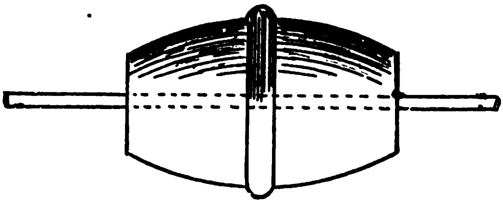

FIG. 1.

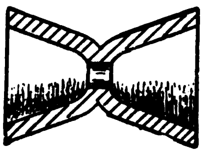

FIG. 2.

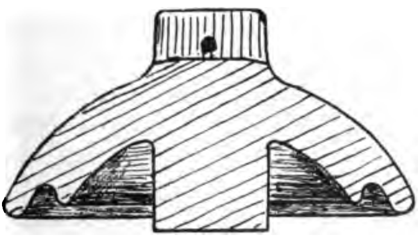

FIG. 3.

used, and which still further reduces the chance of leakage, since it only permits the current to escape in one direction instead of two, as is the case with the two other insulators.

CHAPTER II.

Conductors.—Relative Advantages of Different Materials.—Copper Wire.—Resistance.—Temperature Co-efficient.—Weight and Breaking Strain.—Effects of Rise of Temperature.—Mr. Kennelly's Experiments.—Insulated Conductors in Casing.—Copper Wire Tables.—Conductors Suspended Indoors.—Overhead Conductors.—Fall of Pressure.—Limiting Distance for each Pressure.—Effect of Increase of Pressure. — Feeders. — Fall of Pressure with Alternating Currents.—Virtual Resistance of Conductors with Alternating Currents.

When an electric current is flowing in any circuit, there is a continual expenditure of energy required to force it through against the resistance of the conductor, and this is accompanied by a fall of pressure along the line. This electrical energy is converted into heat energy, and so far as useful effect is concerned is absolutely wasted; so that it is desirable to reduce this expenditure of energy as much as possible, and not only is this so on account of the direct waste, but also because the rise of temperature of the conductor due to the heat generated by the current is itself harmful, causing an increase of resistance, and in some cases damaging the insulating covering, or even fusing the conductor; and further because the fall of pressure along the line cannot in most systems of distribution be allowed to exceed a certain small percentage of the pressure of supply, without giving rise to unsatisfactory results in the working of the receiving apparatus. For any given current, the waste of energy and the fall of pressure both vary directly with the resistance of the conductor; and this resistance varies with the material employed, and for the same material is proportional to the quotient of the length by the sectional area of the conductor.

The choice of a material is, however, influenced by

other considerations besides its specific resistance, such as the cost per unit weight of the material, and its specific gravity and breaking strain; since what is wanted is a conductor which, when insulated and erected in place, shall combine the smallest cost with the lowest resistance; and we shall see, when we come to the consideration of the insulation and erection of conductors, that the cost of these operations may be very materially affected by the relative values of the specific gravity and tensile strength of the metal or alloy which is used.

For the purpose of comparison, these data are given in the following table for various materials which have been used or proposed for use as electrical conductors.

TABLE I.

Material.	Conductivity. Pure Copper =100.	Specific Gravity.	Breaking Weight per Square Inch. lbs.	Wire with a resistance of 1 ohm per 1,000 yards at 32° Fahr.	
				Weight. lbs.	Diameter. inches.
Soft Copper . . .	98	8·9	30,000	267	·171
Hard drawn Copper	97	8·9	64,000	270	·172
Galvanized Iron .	14	7·7	55,000	1632	·456
Cast Steel . . .	10·5	8·0	130,000	2260	·527
Aluminium . . .	55	2·6	26,000	140	·230
Silicon Bronze . .	97	8·9	64,000	273	·174
" " . .	80	8·9	76,000	330	·191
" " . .	45	8·9	110,000	587	·255

For continuously insulated conductors, the conductivity for equal sectional areas is the thing to be looked to; and if the conductor is so fixed that it is not subjected to tensile strain, soft copper is the best material; but if, for instance, the insulated conductor is to be suspended overhead without a bearer wire, so that

tensile strength is important, then hard-drawn copper or the best conducting quality of silicon bronze may be preferable. When a bare wire is suspended overhead, what is wanted is the greatest strength and conductivity for a given weight per unit of length; and if we take, as a coefficient for comparison, the product of the breaking weight and conductivity divided by the specific gravity, we find that hard-drawn copper, silicon bronze, and aluminium give the best results. The last named has been proposed as a suitable material on account of its lightness, as weight for weight it has nearly twice the conductivity of copper; but although the weight might be less, there would be no saving in the cost of poles, owing to the larger surface exposed to wind pressure. The second and third qualities of silicon bronze have the disadvantage of greater bulk and weight than either hard-drawn copper or the first quality of silicon bronze, and these latter are therefore the best materials to use. Iron or steel wire, although cheaper than copper, cannot compete with it, as their coefficients are respectively about one-seventh and one-fourth of that of hard-drawn copper, and their enormous weight and bulk would necessitate a greater expenditure on the supports.

In the early days of telegraphy copper wire was much dearer than at present, and could only be obtained with a conductivity of 30 to 40 per cent. of that of pure copper, and a breaking strain of about 30,000 pounds per square inch; and there were therefore great inducements to seek for a better material in the shape of compound wires, such as copper with a silver core to increase the conductivity, or with an iron core to increase the breaking strain. Owing to the great improvements which have been made of late years in commercial copper wire, such combinations are now of

no value; and, at the present time, copper has practically no rival which can compete with it as a conductor of electricity, and we shall therefore assume in what follows that the conductor is a copper wire of say 98 per cent. of the conductivity of pure copper. Since a rise of temperature increases the resistance of any conductor, we must correct for this as well as for the percentage conductivity of the wire, and for this purpose we must know the temperature coefficient, that is, the number by which we must multiply the resistance of any wire at 32° Fahr. to get its resistance at a temperature of $t°$.

Until recently the rise of temperature has been taken as following a logarithmic law, and most of the correction tables used in submarine cable work are calculated from the formula $R_t = R_{32}\,(1{\cdot}00212)^{t-32}$; but more recent determinations seem to show that a straight line law is equally accurate, and that the resistance R_t of a wire at $t°$ may be calculated from that of the same wire at 32° by the formula

$$R_t = R_{32}\,\{1 + {\cdot}00222\,(t-32)\}.$$

Now the resistance at 32° Fahr. of a soft annealed wire of pure copper one foot long and one-thousandth of an inch in diameter is, according to Mattheisson's standard, 9·583 ohms; and if we assume an average working temperature of 80° Fahr., and a conductivity of 98 per cent., the resistance of a similar wire is equal to $9{\cdot}583 \times \frac{100}{98} \times \left\{1 + (48 \times {\cdot}00222)\right\} = 10{\cdot}82$ ohms.* From this we can obtain a convenient general expression for the resistance in ohms of a copper wire in terms of its dimensions; for instance, $R = \frac{32{\cdot}5\,l}{10^6\,d^2} = \frac{25{\cdot}5\,l}{10^6\,a}$, where l is the length of the conductor in yards, d the diameter in inches, a the sectional area in square inches, and R the

* See Appendix, note A.

resistance in ohms at 80° Fahr. Similar expressions may be given for determining the weight and breaking strains, thus $W = 9{\cdot}09\ ld^2 = 11{\cdot}57\ la$, where W is the weight in pounds, and l, d, and a have the same meaning as before; and

$$\text{B.W.} = 23500\ d^2 = 30000\ a \text{ for soft copper, and}$$
$$\text{B.W.} = 50000\ d^2 = 64000\ a \text{ for hard copper,}$$

where B.W. is the breaking weight in lbs., and d and a are expressed as before in inches.

Having decided on copper as the material to be used, we can now proceed to consider the best proportions to be given to the conductor in order that it may fulfil the following conditions; viz., moderate rise of temperature due to the current, moderate fall of pressure, and economy in working. These three conditions cannot always be fulfilled simultaneously in all systems of distribution; and we therefore propose to consider each one separately, and then to see what is the best arrangement of conductors to suit all three under the various conditions of supply.

Rise of Temperature.

The permissible rise of temperature in an electrical conductor is limited by three considerations, viz., that a rise of temperature increases the resistance of the conductor, and consequently the waste of energy; that it lowers the resistance of the insulating material with which the conductor is covered, and, if excessive, may permanently injure the insulating qualities of the covering; and that it may be the cause of fire if the conductor is in close proximity to combustible material. The increase of resistance of copper conductors, due to rise of temperature, is about one-fifth of one per cent. for each degree Fahrenheit; the exact relation between the resistances of the same conductor at temperatures

of t° and $t_1{}^\circ$ Fahrenheit being expressed by the formula $Rt_1 = Rt\frac{1 + \cdot 00222(t_1 - 32)}{1 + \cdot 00222(t - 32)}$; for instance, suppose the resistance of any conductor is 0·1 ohms at 60° Fahrenheit, it will be increased if the temperature is raised 50°, that is to 110° Fahrenheit, to $0{\cdot}1 \times \frac{1{\cdot}1732}{1{\cdot}0622} = 0{\cdot}1105$, or an increase of 10½ per cent.; and with the same current flowing through it the waste of energy will be 10½ per cent. greater at the higher temperature. The effect of a higher temperature on the insulating covering of a conductor varies very much according to the nature of the material used; but in all cases the insulation resistance is lower at the higher temperature, and in some the insulating material is softened, which is a much more serious defect; since it allows the conductor to sink through the dielectric, permanently injuring the cable, and in time perhaps working its way right through and making contact with the supports on which the cable is carried.

The rise of temperature of any conductor depends on the rate at which energy is expended in heating it, that is, on the product of the square of the current into the resistance; and on the facilities afforded for getting rid of the heat, which in turn depend on the amount of surface exposed, and on the disposition of the conductor with reference to its surroundings. It is evident that the rate at which heat is produced and the rate at which it is dissipated must be equal if the temperature is to remain constant. There are three ways in which the conductor may part with its heat, viz., by radiation, conduction, and convection; and the relative values of each of these for preventing a rise of temperature depend on the local conditions under which the conductor is operated.

Mr. A. E. Kennelly, in 1889, carried out a series of tests for the purpose of determining under practical conditions the laws which govern the relation between current, diameter, and rise of temperature; and as these tests are probably the most complete of any that have yet been made, a brief résumé of the results arrived at will be given. Tests were made on insulated conductors laid in wood casing, on bare copper wires indoors suspended in still air, and on bare and insulated wires suspended out of doors. Conductors in wood casing heated by a current are cooled by conduction through their insulating coverings, the casings, and walls of the room; and, when the outside of the casing has risen in temperature, by radiation and convection from its surface. Under such conditions it was not likely that any simple law would be found to express the relation between current, diameter, and rise of temperature, and this proved to be the case; the results showing, however, that the rise of temperature varies very nearly as the square of the current for any given wire; and that for a given rise of temperature, no serious error is made by assuming that the square of the current varies as the cube of the diameter of the wire. Mr. Kennelly published a table of safe currents for solid wires of various diameters, based on the rule proposed by the Committee of the Institution of Electrical Engineers, that "The conductivity and sectional area of any conductor should be so proportioned to the work it has to do that if double the current proposed be sent through it the temperature of such conductor shall not exceed 150° Fahrenheit." Assuming an average temperature of 75° Fahrenheit, that is equivalent to saying that the rise of temperature shall not exceed 75° with double the normal current; and the rule he gives to

fulfil this condition is $d = \cdot 0147 \sqrt[3]{C^2}$, where d is the diameter of the conductor in inches, and C the current

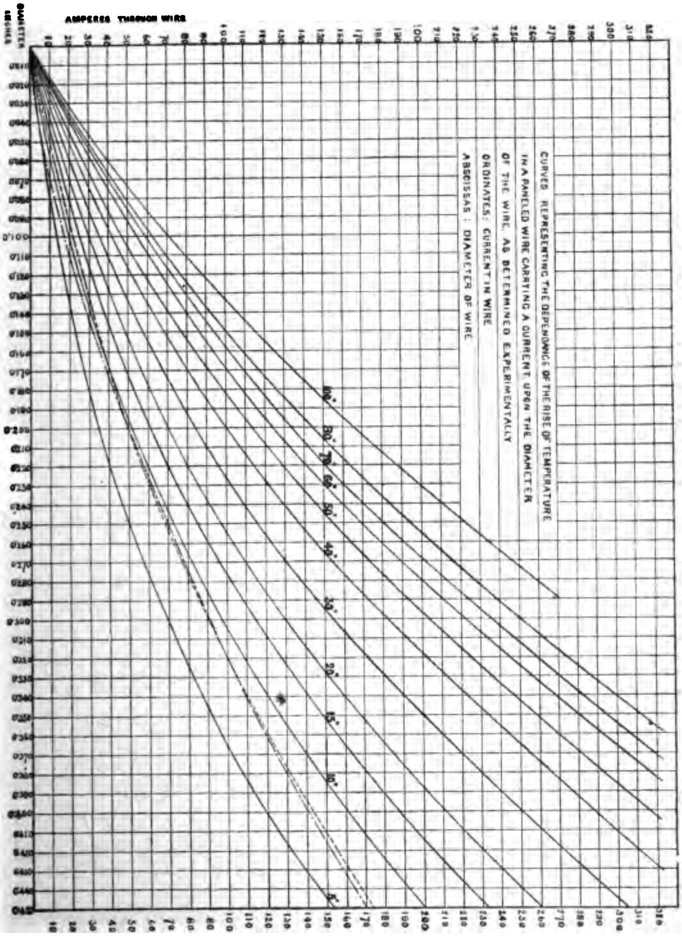

FIG. 4.

in amperes. The curves representing his experimental results are reproduced in Figure 4; and in Table II.,

TABLE II.

Legal Standard Gauge of Wire.	Diameter of Wire.		Area of Wire.		Weight of Copper.		Resistance at 80° Fahr. 98% conductivity.		Current which will raise temperature. Wire in Casing.		Current which will raise temperature. Wire Overhead.		Volts lost per 1000 yards with current in column *
	Inches.	Millimetres.	Square Inches.	Square Millimetres.	lbs. per 1000 yards.	Kilograms per Kilometre	per 1000 yards.	per Kilometre.	18° Fahr. *	50° Fahr.	18° Fahr.	50° Fahr.	
18	·048	1·22	·0018	1·17	20·9	10·4	14·09	15·41	6	10	15	24	84
17	·056	1·42	·0025	1·59	28·5	14·1	10·35	11·32	7	12	18	29	72
16	·064	1·63	·0032	2·08	37·2	18·5	7·925	8·667	9	15	21	35	71
15	·072	1·83	·0041	2·63	47·1	23·4	6·262	6·848	11	18	25	40	69
14	·080	2·03	·0050	3·24	58·2	28·9	5·072	5·547	13	21	29	46	66
13	·092	2·34	·0066	4·29	77·0	38·2	3·835	4·194	16	26	35	56	61
12	·104	2·64	·0085	5·48	98·3	48·8	3·001	3·282	19	31	41	66	57
11	·116	2·95	·0106	6·82	122	60·7	2·412	2·638	22	36	47	77	53
10	·128	3·25	·0129	8·30	149	73·9	1·981	2·167	26	42	54	88	51
9	·144	3·66	·0163	10·5	188	93·5	1·565	1·712	31	50	64	103	49
8	·160	4·06	·0201	13·0	233	115	1·268	1·387	36	59	74	119	46
7	·176	4·47	·0243	15·7	282	140	1·048	1·146	41	68	85	137	43
6	·192	4·88	·0290	18·7	335	166	·8806	·9630	47	77	96	154	41
5	·212	5·38	·0353	22·8	409	203	·7222	·7899	55	90	110	178	40
4	·232	5·89	·0423	27·3	489	243	·6031	·6595	62	103	125	202	37
3	·252	6·40	·0499	32·2	577	286	·5112	·5590	71	116	141	227	36
2	·276	7·01	·0598	38·6	692	344	·4261	·4660	81	133	160	258	34
1	·300	7·62	·0707	45·6	818	406	·3607	·3944	92	151	180	291	33

No. of Wires in Strand.	Legal Stand. and Gauge of each Wire.	Diameter of Single Wire.		Diameter of Strand.		Equivalent Area of Strand.		Weight of Copper.		Resistance at 80° Fahr. 98% conductivity.		Current which will raise temperature.				Volts lost per 1000 yards with current in col. *
												Wire in Casing.		Wire Overhead.		
		Inches.	Milli-metres.	Inches.	Milli-metres.	Square Inches.	Square Milli-metres.	lbs. per 1000 yds.	Kilograms per Kilometre.	per 1000 yards.	per Kilo-metre.	18° Fahr. *	50° Fahr.	18° Fahr.	50° Fahr.	
7	25	·020	·508	·060	1·52	·0022	1·42	25·6	12·7	11·59	12·68	7	12	17	28	81
7	23	·024	·609	·072	1·83	·0032	2·04	36·9	18·3	8·051	8·805	10	15	22	36	80
7	22	·028	·711	·084	2·13	·0043	2·78	50·6	25·1	5·915	6·469	12	19	27	44	71
7	21½	·030	·762	·090	2·29	·0049	3·19	58·0	28·8	5·151	5·635	14	22	30	48	72
7	20½	·033	·838	·099	2·51	·0060	3·86	70·5	35·0	4·258	4·657	16	25	34	55	68
7	20	·036	·914	·108	2·74	·0071	4·59	83·5	41·5	3·578	3·913	18	28	38	61	64
7	19	·040	1·02	·120	3·05	·0088	5·72	103	51·3	2·898	3·170	21	33	44	71	61
7	18	·048	1·22	·144	3·66	·0127	8·18	149	73·7	2·013	2·201	27	44	56	91	54
7	17	·056	1·42	·168	4·27	·0172	11·1	202	100	1·479	1·617	34	55	70	113	50
7	16	·064	1·63	·192	4·88	·0225	14·6	264	131	1·132	1·238	42	68	84	136	47
7	15	·072	1·83	·216	5·49	·0285	18·4	335	166	·8945	·9783	50	81	100	160	45
7	14	·080	2·03	·240	6·10	·0352	22·6	413	205	·7246	·7924	59	95	116	186	43
19	20	·036	·914	·180	4·57	·0193	12·5	228	113	1·318	1·442	38	61	77	124	50
19	19	·040	1·02	·200	5·08	·0239	15·5	282	140	1·068	1·168	45	72	89	144	48
19	18	·048	1·22	·240	6·10	·0344	22·2	406	201	·7415	·8109	59	95	116	186	44
19	17	·056	1·42	·280	7·11	·0468	30·2	553	274	·5448	·5958	74	120	144	232	40
19	16	·064	1·63	·320	8·13	·0611	39·5	722	358	·4171	·4562	90	146	175	281	38
19	15	·072	1·83	·360	9·14	·0773	50·0	914	453	·3296	·3604	108	174	207	333	36
19	14	·080	2·03	·400	10·2	·0955	61·5	1128	560	·2669	·2919	126	205	241	388	34
19	13	·092	2·34	·460	11·7	·1263	81·7	1493	740	·2018	·2207	156	252	295	476	31
19	12	·104	2·64	·520	13·2	·1614	104	1907	946	·1580	·1727	187	303	353	569	29
37	16	·064	1·63	·448	11·4	·1190	77·2	1411	700	·2142	·2342	150	243	284	458	32
37	15	·072	1·83	·504	12·8	·1506	97·3	1786	886	·1692	·1851	179	290	337	544	30
37	14	·080	2·03	·560	14·2	·1860	120	2205	1094	·1371	·1499	210	339	394	634	29
37	13	·092	2·34	·644	16·4	·2459	159	2916	1446	·1036	·1133	258	418	482	777	27
37	12	·104	2·64	·728	18·5	·3143	203	3726	1848	·0811	·0887	311	503	578	932	25
61	13	·092	2·34	·828	21·0	·4055	262	4816	2389	·0629	·0688	377	610	700	1126	24
61	12	·104	2·64	·936	23·8	·5182	334	6154	3052	·0492	·0538	453	733	838	1350	22

printed on pages 20 and 21, which gives the particulars of the various solid and stranded conductors in general use, the safe current for each in accordance with this rule is given, as also an approximate value of the current that would be required to raise the temperature 50° Fahrenheit.

The formula $d = \cdot 0147 \sqrt[3]{C^2}$ may also be written $C = 560 \sqrt{d^3}$, and either may be used for calculating the proper relation between current and diameter for solid wires. When stranded conductors are used, it must be remembered that their resistance is about 30 per cent. greater than that of a solid conductor of the same length and diameter, owing to the loss of space in stranding; and therefore the formula given above must be modified so as to take this into account. It is evident that the same amount of heat will be generated, whether a current C is passed through a resistance R, or a current $\frac{C}{\sqrt{1 \cdot 30}}$ is passed through a resistance 1·30 R; and therefore for stranded wires the constant 560 must be divided by $\sqrt{1 \cdot 30}$, giving approximately $C = 500 \sqrt{d^3}$; and the constant ·0147 must be multiplied by $\sqrt[3]{1 \cdot 30}$, making the formula, say, $d = \cdot 016 \sqrt[3]{C^2}$.

Bare conductors suspended in still air indoors are cooled by radiation and convection. The amount of heat that is dissipated by radiation depends on the nature of the surface (a properly blackened copper wire radiating heat at about twice the rate of a bright one), on the extent of surface exposed, and on the temperature difference. For the same wire, Mr. Kennelly found that the heat radiated per unit surface might be expressed by the equation $h = c \times \{(1 \cdot 0077)^t - 1\}$, where c is a constant and t is the temperature difference in degrees centigrade. The actual value of h in watts

per square inch of surface, calculated from his figures for bright copper, is ·035 for a temperature difference of 18° Fahr., and ·104 for one of 50° Fahr. The total radiation from any bright copper wire is therefore $H_r = \cdot035\,\pi dl = \cdot110\,dl$ for 18° Fahr., and $H_r = \cdot104\,\pi dl = \cdot327\,dl$ for 50° Fahr., d and l being respectively the diameter and length of the wire in inches. A useful approximation, and one that will not lead to any serious error, with any temperature rise that is allowed in practice, is that the heat radiated per linear yard of conductor $= \cdot22dt$ where d is the diameter in inches, and t the temperature rise in degrees Fahr. In still air convection was found to be nearly proportional to the temperature rise, and to increase slightly with the diameter of the wire; but it appeared that for ordinary practice it might be taken at ·00175 watts per linear centimetre per degree centigrade, which is equivalent to ·088 watts per linear yard per degree Fahrenheit, or $H_c = \cdot088t$ watts. The sum of the radiation and convection $H_r + H_c$ must equal the heat produced C^2R, when the final temperature is reached; and since, assuming the air temperature to be 80° Fahrenheit, the resistance of one yard of any conductor can be expressed very nearly by $R = \frac{32\cdot5(1 + \cdot00222t)}{10^6 d^2}$

$$C^2 = \frac{10^6 \times d^2 t}{32\cdot5(1 + \cdot00222t)}(\cdot22d + \cdot088)$$

or say $C = 80d\sqrt{\frac{t(d + \cdot4)}{(1 + \cdot00222t)}}$ for bright copper wires.

If the radiation from a blackened surface is taken as twice that from a bright one, then

$C = 80d\sqrt{\frac{t(2d + \cdot4)}{(1 + \cdot00222)t}}$ will give the current for a blackened copper wire.

When the wire, as is more generally the case, is

suspended out of doors, the effect of convection is considerably increased, especially if any wind is blowing. In calm weather the results obtained by Mr. Kennelly showed that, to obtain the total emissivity of the wire, it was necessary to add a term to the value of the convection, which varied with the diameter of the wire; and that under these conditions the convection per linear centimetre and per degree centigrade was equal to $(\cdot 00175 + \cdot 013d)$ watts, which is equivalent to $(\cdot 088 + 1\cdot 68d)$ watts per linear yard per degree Fahr., or $H_c = (\cdot 088 + 1\cdot 68d)t$ watts, when d is the diameter in inches and t the temperature rise in degrees Fahr. This gives the total emissivity per yard for bright wires $H_r + H_c = (\cdot 088 + 1\cdot 9d)t$, and equating this to C^2R, and assuming an air temperature of 60° Fahr., we get $C^2 = \frac{10^6 \times d^2 t}{31\cdot 1(1 + \cdot 00222t)}(\cdot 088 + 1\cdot 9d)$ or $C = 247d\sqrt{\frac{t(d + \cdot 046)}{(1 + \cdot 00222t)}}$. If the wires are blackened, they will carry a rather larger current, but owing to the greater importance of convection the increase will probably not exceed five per cent., the equation for blackened wires being

$$C = 260d\sqrt{\frac{t(d + \cdot 041)}{(1 + \cdot 00222t)}}.$$

From the equation for bright wires, the relation between current and diameter for temperature rises of 18° and 50° Fahr. has been calculated for the ordinary solid and stranded conductors, and the results are embodied in Table II.; allowance being made for the stranding in the same way as before, which reduces the constants 247 and 260 to 217 and 230 respectively.

Fall of Pressure.—The second condition which must be fulfilled by the conductor has reference to

the fall of pressure along it when a current is flowing. With some systems of distribution the fall of pressure is of no special moment; but when a number of lamps are being supplied in parallel circuit, it is of the utmost importance that the pressure at the lamp terminals shall not vary more than a certain percentage; and, since any variation of pressure at the lamps results in a still larger variation in illuminating power, this percentage must be a small one, certainly not exceeding 4 or 5 volts for a 100 volt lamp. The fall of pressure is measured by the product of the current into the resistance of the conductors leading from the dynamo to the lamps and back to the dynamo again; and this product CR must not be more than say 0·04 E, when E is the pressure of supply; but R varies as $\frac{l}{a}$ and since, with a fixed current density, C varies as a, the product CR will be proportional to the length of the conductor; *i.e.*, to the distance between the dynamo and the lamps.

We therefore see that for each pressure of supply, when once the current density or ratio $\frac{C}{a}$ is settled, there is a definite maximum distance between the dynamo and the farthest lamp, which cannot be exceeded without a greater fall of pressure than is permissible; and further, that this distance is, other things being equal, proportional to the working pressure. For a working pressure of 100 volts this gives a permissible variation of 4 volts between the pressure at the lamp terminals with full current and that with one lamp only, and the maximum distance is given by the equation $L = 78a$, where L is the distance in yards from the dynamo to the farthest lamp, and a is the area in square inches which should be used for a

maximum current of 1,000 amperes. In actual practice it generally happens that the conductor has not to carry the maximum current the full distance of L yards as supposed above, but that lamps are branched off all along the conductor from the dynamo to the farthest lamp. In such a case, if we suppose a uniform distribution of the lamps, the current may be taken as decreasing by a fixed amount, say a amperes, per yard; and the fall of pressure is then equal to the product of the resistance of two yards of conductor into the sum of the currents in each yard of the circuit. The resistance of two yards of conductor is equal to $\frac{51}{10^6 a}$, and the sum of the currents is equal to $\frac{aL(L+1)}{2}$ or $\frac{C(L+1)}{2}$, since $C = aL$. The fall of pressure is therefore equal to $\frac{25 \cdot 5\, C(L+1)}{10^6 a}$ or $\frac{25 \cdot 5\, D(L+1)}{10^6}$ where D is the current density at starting from the dynamo. If we again take a fall of 4 volts and a current density of 1,000 amperes per square inch,

$$L = \frac{4 \times 10^6}{25 \cdot 5 \times 1000} - 1 = 156 \text{ yards.}$$

In isolated plants for the lighting of houses or ships, where a common practice is to work with a maximum current density of about 1000 amperes per square inch, and when the distance from the dynamo to the farthest lamp is small, there is generally no difficulty in keeping well within the permissible limits of variation; but when the lamps are distributed over an extended area, as in the case of a central station supply, it is impossible to comply with this rule of variation of pressure on a simple 100 volt parallel system, without using conductors which are much larger than the economical size; and since economy is of the first

importance, it is necessary to adopt special measures to bring the two conditions into line, by increasing the pressure of supply, or the number of points of supply, or using a combination of both. An increase of pressure will be accompanied by a proportionate decrease in current for the same output in watts, but the economical area will also be decreased in proportion, so that the fall of pressure in volts per yard will be the same. Since, however, the number of volts variation which will give the same percentage fall is increased in proportion to the pressure, the distance from the dynamo to the lamps may be increased at the same rate; for example, suppose the economical current density to be 800 amperes per square inch, then the fall of pressure may be expressed by

$$\frac{51\,\mathrm{D}\,\mathrm{L}}{10^6} = \cdot0408\,\mathrm{L}$$

if the full current has to be transmitted to a distance of L yards, or by

$$\frac{25\cdot5\,\mathrm{D}\,(\mathrm{L}+1)}{10^6} = \cdot0204\,(\mathrm{L}+1)$$

if lamps are branched off all along the conductor.

In this latter case L = 48 yards for each volt fall of pressure, and therefore if a 4 per cent. drop is permissible, the farthest lamp may be 192 yards away on a 100 volt circuit, or 384 yards on a 200 volt circuit, and so on. The use of high pressures is, however, not possible in a parallel system with the ordinary incandescent lamp, unless the conductors and other distributing apparatus are specially arranged to supply each lamp with a pressure not much exceeding 200 volts; and the extra first cost of, and the waste of energy in this auxiliary apparatus will always tend to reduce the advantages which accrue from increasing the pressure.

The second method of increasing the permissible distance between the dynamo and the lamps, without running counter to the laws of economy or variation of pressure, is that in which a number of distributing points are arranged at comparatively short distances apart; these points being connected with the dynamo by feeder mains, and the pressure at the ends of these feeder mains or distributing points being maintained constant by regulating apparatus fixed in the station. Suppose that a 4 volt drop of pressure is allowable, and that we are working with a current density of 800 amperes per square inch; then the distributing points must be so arranged that no lamp is more than 192 yards distant from some one of them; but the distributing point itself may be, so far as variation of pressure is concerned, at a very much greater distance from the dynamo; the only condition being that the dynamo must be capable of supplying its current at a pressure equal to that required at the distributing point plus the fall of pressure in the feeder main.

The various methods by which current may be distributed over extended areas will be treated more fully under the heading of systems of distribution; but before leaving the subject of fall of pressure, a point connected with the distribution of alternating currents must be noticed, since these latter do not follow exactly the same laws as the direct current, and at times may require a special treatment if accurate results are to be obtained.

When carrying an alternating current there is an increase in the virtual resistance of the conductor, which varies with the rapidity of the alternations and with the diameter of the conductor, and was first pointed out by Lord Kelvin, who supplied figures for calculating its amount under various conditions. From

these figures Mr. Mordey has worked out a table, reproduced below, which shows the increase of virtual over ordinary resistance for various sizes of conductor at three different periodicities, and also the currents that may be carried by each at a current density of

TABLE III.

VIRTUAL RESISTANCE, ETC., OF CONDUCTORS WITH ALTERNATING CURRENTS.

Diameter.		Area.		Increase over Ordinary Resistance.	Current at 450 amperes per sq. in.	Watts at 2,000 volts.	Watts at 100 volts.	∾ per second.
MM.	Inches.	Sq. MM.	Sq. in.					
10	·3937	78·54	·122	less than $\frac{1}{100}$%	55	110000	5500	80
15	·5905	176·7	·274	2½%	133	266000	13300	
20	·7874	314·16	·487	8%	220	440000	22000	
25	·9842	490·8	·760	17½%				
40	1·575	1256	1·95	68%				
100	3·937	7854	12·17	3·8 times.				
1000	39·37	785400	1217	35 times.				
9	·3543	63·62	·098	less than $\frac{1}{100}$%	45	90000	4500	100
13·4	·5280	141·3	·218	2½%	98·5	197000	9850	
18	·7086	254·4	·394	8%	178	356000	17800	
22·4	·8826	394·0	·611	17½%				
7·75	·3013	47·2	·071	less than $\frac{1}{100}$%	32	64000	3200	133
11·61	·4570	106	·164	2½%	74	148000	7400	
15·5	·6102	189	·292	8%	131·4	263000	13140	
19·36	·7622	294	·456	17½%				

450 amperes per square inch, and the corresponding output in watts at 2000 and 100 volts.

From this table it will be seen that the effect only becomes appreciable with fairly large conductors, since 10 per cent. increase of resistance need not mean a fall of pressure of more than perhaps ½ per cent. of the

pressure of supply; and that therefore, for high pressures, there need be no difficulty in subdividing the circuits in such a manner as to avoid all trouble on this score. The inconvenience is, however, much greater with a low pressure distribution, since the limiting number of 16 candle-power lamps on a 100 volt circuit varies from 200 to 400, according to the periodicity; and although the difficulty may be got over, this can only be done at the expense of a greater outlay in distributing mains. The cables may be run entirely separate from one another to form a number of comparatively small circuits, or a number of lightly insulated conductors may be stranded up together into one cable, or the conductor may be made in the form of a tube or strip; the object in all cases being to so arrange the conductor that the distance from any point in its section to the nearest point on the surface shall not exceed, say, a quarter of an inch.

CHAPTER III.

Economy of Working.—Lord Kelvin's Law.—Cost of Electrical Energy.—Load Factor.—Equivalent Current.—Economical Area for given Current.—Economical Current for given Area.—Economical Fall of Pressure for Set of Feeders.—Economical Area for Distributing Mains.—Calculations for Feeders and Distributors.—Example.

SINCE the energy wasted in heating any conductor is measured by the product of the current squared into the resistance, it is evident that it can be reduced indefinitely by reducing the value of the resistance; but, unfortunately, when the length of the conductor is fixed, its resistance can only be decreased by giving it a larger sectional area, and this increases its first cost. Now the annual charge on the conductor is made up of two items, the cost of the energy wasted in it, and the amount which must be put down for interest on capital expended and for depreciation; and the greatest economy is obtained when the sum of these items is as small as possible.

To fix our ideas, let us suppose that we have to transmit for 1,200 hours per annum a current of 100 amperes along a conductor whose length is 1000 yards; that every Board of Trade unit of 1000 watt hours that is wasted in the conductor increases our expenditure by twopence; and that a sum equal to 10 per cent. of the first cost of the line must be allowed for interest and depreciation. Let us first try a conductor of 19/15, which is about as small as the heating of the conductor will allow, then the cost of the line may be

£320, and the resistance ·3296 ohms. The watts wasted will be 3,296, and the watt hours per annum 3,955,200, which at twopence per 1,000 watt hours gives £32 19*s.* If we add to this 10 per cent. on £320, or £32, we get a total annual cost of £64 19*s.* Now let us try a conductor of 19/13, costing £400 laid, and having a resistance of ·2018 ohms. The watt hours per annum will be 2,421,600, costing £20 3*s.* 6*d.*, and interest and depreciation at 10 per cent. on £400 will be £40, giving a total annual cost of £60 3*s.* 6*d.*, or nearly £5 less than with the 19/15 conductor. Let us try a larger conductor still, say a 37/14, having a resistance of ·1371 ohms, and costing £490 laid. The watt hours will be 1,645,200 and will cost £13 14*s.*, but the interest and depreciation will be £49, giving a total of £62 14*s.*, which is more than the cost with the 19/13 conductor. From this we see that there is some conductor between a 19/15 and a 37/14 which will give a minimum value to the annnal cost, and the problem we have to solve is at what point does economy tell us to stop reducing the resistance; or, what is the same thing, increasing the area of the conductor; *i.e.*, at what point will the sum of the annual cost of wasted energy and the annual cost of interest and depreciation be a minimum.

Sir William Thomson (now Lord Kelvin) first drew attention to this question in a paper on "The Economy of Metal Conductors of Electricity," read before the British Association in 1881, and showed that, if the capital outlay on the conductor varied in strict proportion to the weight of metal, then the most economical size of conductor was that for which the annual cost of interest and depreciation was equal to the annual cost of wasted energy. The reasoning by which this result is arrived at is as follows: The annual

cost of waste energy W is equal to the product of the square of the current C, the resistance R, the number of hours t per annum that the current is flowing, and the cost w of one watt hour; or

$W = C^2 R\, tw$, or since $R = \frac{l}{a}$ multiplied by a constant

$W = C^2 \frac{l}{a} tw \times A$ when $A = \frac{R\,a}{l}$. The capital outlay on the conductor K is equal to the weight of metal multiplied by a constant; and since the weight is proportional to la, we may write $K = kla$, where k is a constant; and if p is the fraction of the capital outlay which is to be charged annually for interest and depreciation, we have $pK = pkla$ as the annual expenditure on this account. The total annual expenditure is $p\ K + W = \left(pkal + \frac{C^2 twAl}{a}\right)$ and this will be a minimum when $\frac{d(pkal)}{da} + \frac{d\left(\frac{C^2 twAl}{a}\right)}{da} = 0$. This gives

$pkl - \frac{C^2 twAl}{a^2} = 0$ or $pkal = \frac{C^2 twAl}{a}$; that is, the annual charge for interest and depreciation must equal the annual cost of wasted energy.

The actual relation between a and C is expressed by $a^2 = C^2 \frac{twA}{pk}$ or $a = C\sqrt{\frac{twA}{pk}}$; which shows that if the cost of a watt for all the working hours of the year and the rate of interest and depreciation are constant, then the economical conductor is always worked at the same current density. And since neither the length nor pressure appear in the equation, we see that the economical area is the same for all values of them.

In actual practice the problem of determining the most economical conductor is more complicated than the one worked out above, owing to the fact that the capital outlay on the conductors does not vary in exact proportion with the sectional area of the copper, and also on account of the difficulty of assigning a correct value to the annual cost of the wasted energy. As regards capital outlay, this is made up of the cost of the copper, of the insulation, of the supports or conduit, and of the labour of putting the conductor in place; and it is evident that all these items will not increase in cost in proportion to the area of the conductor. For example, with a continuously insulated cable laid in iron pipe under the footway, the cost of opening up a trench and making the pavement good again will be the same for very wide variations in the size of the conductor, the cost of the iron pipe does not increase nearly as fast as the area of the conductor, and the cost of the insulated cable, although more nearly proportional, is slightly less per unit area as the size increases. With bare conductors supported on insulators in a culvert, the cost of trenching and building the culvert remains practically the same for all conductors up to a joint area of several square inches; and with overhead lines the cost of the poles and insulators will not follow a proportional law, since the same poles would in each case be used for several sizes of conductor.

For each particular system of mains, however, it is possible to divide the cost into two parts without much inaccuracy, one of which will be a constant whilst the other increases in proportion to the area of the conductor; and we will therefore see what difference is made in the expression for the economical area when the capital outlay is equal to $l\ (ka + \mathrm{B})$ instead

of $k\,l\,a$. The total annual expenditure will now be $p\,\mathrm{K}+\mathrm{W}=p\,l\,k\,a+p\,l\,\mathrm{B}+\dfrac{C^2\,t\,w\,\mathrm{A}\,l}{a}$; and this will be a minimum, as before, when $\dfrac{dp\mathrm{K}}{da}+\dfrac{d\mathrm{W}}{da}=0$; that is when $p\,l\,k-\dfrac{C^2\,t\,w\,\mathrm{A}\,l}{a^2}=0$ since the differential coefficient of the constant $\dfrac{d.p\,l\,\mathrm{B}}{d\,a}=0$.

The best value of a is still given by the equation $a=C\sqrt{\dfrac{t\,w\,\mathrm{A}}{p\,k}}$, but k has not the same value as before, since it refers only to that part of the cost which is proportional to the area of the conductor. The law enunciated by Lord Kelvin will now be altered as follows:—The most economical size of conductor is that for which the annual cost of wasted energy is equal to the annual charge for interest and depreciation on that part of the capital outlay which is proportional to the area of the conductor.

To obtain the cost of wasted energy with any degree of accuracy, we must know the cost throughout the year of some unit such as the Board of Trade unit of one kilowatt hour, and the number of units wasted during the year in heating the conductor.

First, as to the cost of the unit, an important question at once arises as to what items of expenditure should be included in this cost for the present purpose. The total cost of a unit delivered to the customer is made up of the cost of fuel, water, oil, and petty stores, of labour and station supervision, of general management expenses, and of the annual charge for maintenance and depreciation on the whole plant. At first sight it may appear fair to include all these items, with the exception of that proportion of them which

belongs to the conductors themselves; but, on the other hand, it may be argued that the cost of material is really the only thing which will vary with the varying amount of waste energy in the conductors, and that the other charges will remain practically the same whether the output of the station is increased by two or three per cent. due to this waste or not. This question is a most important one, since the value of the result of the calculation depends on the accuracy with which the cost of the unit can be determined, and it will therefore be well to consider the reasons for adopting one method or the other.

In the design of a station, when the number of dynamo machines has been decided on, it is usual to make them of such capacity that they can together supply current for the maximum demand, plus an allowance for reserve, and that each can supply its current at such a pressure as will provide for the loss in the longest feeders which can be required in the district; and then to provide means of reducing that pressure as required by lowering the speed or adjusting the field strength. This being so, it is evident that so long as no mistake has been made in the estimate of the maximum pressure required at any station, the first cost of the dynamo machines is not affected by a variation in the amount of energy wasted in the conductors. In a similar manner engines and boilers are put in of equivalent capacity, and the building and fittings are arranged for the maximum output, and therefore the first cost of none of these items is appreciably affected by the amount of wasted energy. The annual cost of station supervision and general management is practically independent of this variation in output, and so is the labour in the engine room, since it is only a question of running

the dynamos a volt or two higher or lower as the case may be. The depreciation on the actual generating plant may be slightly increased owing to its being worked at a greater output, and therefore it would appear to be right to make allowance for this, but it is very doubtful whether even this would be increased at anything like a proportional rate. When we consider that what we want to get is the actual increase of expenditure on account of the energy wasted in conductors, so that it may be balanced against the annual charge for interest and depreciation on them, it seems right in most cases to put on one side all the expenses connected with management, supervision, labour, and depreciation of buildings and fittings, and to include in the cost of the unit only the extra expenditure on fuel, water, oil, petty stores, and depreciation on the generating plant.

The cost of these several items will vary very much with the conditions of supply and with local circumstances, and the engineer must therefore make a separate calculation for each particular case; the most important causes of the variation being the cost of the fuel and the load factor, or relation which the actual output of the plant bears to the maximum possible output, *i.e.*, the output which would be obtained if the plant were worked continuously at full load for the period under consideration. The name load factor was suggested for this ratio by Mr. Crompton in his paper on "The Cost of the Generation and Distribution of Electrical Energy," read before the Institution of Civil Engineers; and in this paper great stress was laid on the important part which the load factor plays in determining the cost, and much information was given in the shape of tables and diagrams which should be very useful to all those

engaged in the erecting or working of central station plants.

An examination of the costs of the various companies and corporations supplying electricity will enable us to fix on a fair average cost of the energy wasted in the conductors; and the values of w used in the examples given later on are based on the actual costs of fuel, water, oil and petty stores per unit, with a small amount added for the proportion of depreciation on the generating plant which is chargeable to energy wasted in conductors. The average cost thus calculated from the published figures of over sixty undertakings comes out a small fraction under one penny farthing per 1000 watt hours, and we propose therefore to take w as ·0012 pence or ·000005 pounds.

When the average cost throughout the year of a unit has been calculated, the next point to settle is the number of such units which will be wasted during the year in heating the conductor. In a constant current system the data required are simply the value of the constant current, and the number of hours in the year during which the plant is working; but in a constant pressure system, where the current is continually changing according to the varying requirements of the consumers at different times of the day and seasons of the year, it is necessary, so as to take into account these variations, to sum up the instantaneous values of the waste energy, and from them to calculate the value of a current which, if maintained continuously, would give the same waste. To do this requires a knowledge of the probable load curve, that is, the curve which shows the output of current at any time during the period under consideration; and, from the data now being furnished by more than 100

stations at work in the United Kingdom, we may fairly expect to get figures which will enable us to make a tolerably correct estimate of the load curve for any new undertaking.

To calculate the ratio e of the equivalent current to the full load current from the load curve, we take a series of currents $C_1, C_2, C_3, \ldots C_n$, gradually increasing from zero up to the maximum, and for each current we find from the load curve the number of hours $t_1, t_2, t_3 \ldots t_n$ in the year during which it is flowing; then the total waste is evidently represented by $R\,(C_1^2t_1 + C_2^2t_2 + C_3^2t_3 + \ldots + C_n^2t_n)$, and since by definition this is to be equal to $R\,(eC_n)^2t$, where eC_n is the equivalent current and $t = (t_1 + t_2 + t_3 + \ldots + t_n) =$ the total number of hours during which the plant is working, the value of e is given by the equation—

$$e = \sqrt{\frac{C_1^2t_1 + C_2^2t_2 + C_3^2t_3 + \ldots + C_n^2t_n}{C_n^2t}}.$$

It may be well here to draw attention to a difference between the values of e for direct and alternating currents when the curves representing the energy delivered to consumers are the same; a difference which arises from the fact that in an alternating current circuit the output in watts is not necessarily measured by the product of the volts into the amperes, as is the case in a direct current circuit, and also that whenever transformers are used, there is a certain amount of current required for exciting them whether the secondary circuits are loaded or not.

For example, when open circuit transformers are used, which require a large exciting current (as much as 30 per cent. of the maximum current according to figures given by Mr. Swinburne of his own transformer), the curve of output of current will be very

different from that obtained with the same variation of load on a direct current circuit; since in the former case the current can never fall below 30 per cent. of the maximum, even at times when no lamps are lighted, whereas in the latter case the equivalent current itself is rarely as high as 30 per cent. of the maximum. With closed circuit transformers, the exciting current is very much less, but in this case also there is an appreciable increase in the value of the equivalent current.

With regard to the question of the annual charge for interest and depreciation which has to be equated to the annual cost of waste energy, the former must entirely depend on the financial conditions of the supply company. The allowance for depreciation will depend on the type of conductor and the method in which it is supported overhead or laid underground, and at present it is not possible to assign accurate values to the depreciation for the various methods of line construction, since their employment is of such recent date that there are very few figures to work on.

The following examples will clearly show how the calculations should be made when the data are determined on, and may be taken as representing fair examples of two of the most important kinds of distribution with which one has to deal. (1) Suppose a main is to be laid in connection with a central station, and that an examination of the load curves for a year at this or any other station working under like conditions, has shown that the probable variation of output will be as follows:—The maximum current, say 200 amperes, will be required for 50 hours, 180 amperes for 100 hours, 160 amperes for 150 hours, 140 amperes for 150 hours, 120 amperes for 200 hours, 100 amperes

for 200 hours, 80 amperes for 350 hours, 60 amperes for 500 hours, 40 amperes for 1,000 hours, 20 amperes for 3,000 hours, and 10 amperes for 3,060 hours. Let us further suppose that rubber cables are to be used drawn into cast-iron pipes, and that in the expression $(ka+\mathrm{B})$ for the cost per yard of conductor laid $k=$ £·775 and B = £·25; also that it has been settled that 10 per cent. shall be allowed for interest and depreciation.

From these figures we can find the values of the several constants in the equation $a=\mathrm{C}\sqrt{\dfrac{tw\mathrm{A}}{pk}}$ as follows:—

$t=$ total working hours $=8{,}760$.
$w=$ cost of one watt hour $=£5\times10^{-6}$.
$\mathrm{A}=\dfrac{\mathrm{R}a}{l}=25{\cdot}5\times10^{-6}$.
$p=\cdot1$
$k=£{\cdot}775$.
$\mathrm{C}=e\mathrm{C}_n$ where $\mathrm{C}_n=$ full load current $=200$ amperes and

$$e=\sqrt{\frac{50(200)^2+100(180^2)+150(160^2)+150(140)^2+200(120)^2+200(100)^2+350(80)^2+500(60^2)+1000(40)^2+3000(20)^2+3060(10)^2}{8760(200)^2}}$$

which gives—

$$e=\sqrt{\frac{24046000}{350400000}}=\cdot262 \text{ and } \mathrm{C}=52{\cdot}4.$$

Filling in these values in the equation we get—

$$a=52{\cdot}4\sqrt{\frac{8760\times5\times25{\cdot}5}{\cdot1\times\cdot775\times10^{12}}}=\cdot1985 \text{ square inches}$$

which gives for the full load current a density of, say, 1,000 amperes per square inch.

(2) Suppose a main is to be laid for a power supply

where the load is constant at 200 amperes, and the plant is in use for 3,000 hours per annum. Since the load factor is 100 per cent., and therefore the generating plant is working at its maximum efficiency, the cost of a watt hour should be somewhat smaller, and we will therefore take it as £4×10^{-6} instead of £5×10^{-6}. Suppose the line to be a bare wire overhead, so that the portion of the cost that varies with the area of the conductor is practically the cost of the conductor itself, which we may take at the rate of eight shillings per yard per square inch of section, and let 10 per cent. again be allowed for interest and depreciation: we have the following values:—$C = 200$, $t = 3{,}000$, $w =$ £4×10^{-6}. $A = 25{\cdot}5 \times 10^{-6}$ and $p\,k =$ £$\cdot 04$. Putting in these values in our equation, we get—

$$a = 200\sqrt{\frac{3{,}000 \times 4 \times 25{\cdot}5}{\cdot 04 \times 10^2}} = \cdot 553 \text{ square inches,}$$

which gives a current density of only 362 amperes per square inch

To save the labour of working out each separate case, Professor Forbes prepared some tables, which he published in 1885, in his Cantor Lectures on "The Distribution of Electricity." These tables are so arranged that they show the economical area of conductor per thousand amperes when the cost of laying an additional ton of copper (*i.e.*, that portion of the total cost which varies proportionately with the area of copper), the rate for interest and depreciation, and the annual cost of an electrical horse-power, are known. In Table IV. each vertical column is headed by a possible cost of laying an additional ton of copper, and against each horizontal row is given a possible percentage rate to be allowed for interest and depreciation; the choice of the proper values having to be determined by the engineer in accordance with the con-

ditions of the case he is dealing with. In Table V. each horizontal row is appropriated to a possible annual cost of one electrical horse-power, and each vertical column is headed by a figure representing the area in square inches which should be used per thousand amperes. To explain the method of using these tables, it will be best to take an example: Suppose a current of 100 amperes is to be used, that the cost of laying an additional ton of copper is £200, that 10 per cent. is to be allowed for interest and depreciation, and that the electrical horse-power costs £20 per annum. Looking in Table IV. along the horizontal row of figures opposite 10 per cent. until we come to the column headed £200, we find the figure 1·029. Turning now to Table V. we look along the horizontal row opposite £20 until we find the number most nearly equal to 1·029, in this case 1·018; the figure which heads this vertical column, namely 2·6, is the proper area of conductor for a

TABLE IV.—*Cost of Laying one additional Ton of Copper.*

—		£60	£65	£70	£75	£80	£85	£90	£95	£100	£110	£120
Percentage allowed for interest and depreciation per annum.	5	·154	·167	·180	·193	·206	·219	·231	·244	·257	·283	·309
	7½	·231	·251	·270	·289	·309	·328	·347	·366	·386	·424	·463
	10	·308	·334	·360	·386	·411	·437	·462	·488	·514	·565	·617
	12½	·385	·418	·450	·482	·515	·546	·578	·610	·643	·707	·772
	15	·463	·501	·540	·578	·617	·656	·694	·733	·771	·849	·92[illegible]
	20	·616	·668	·720	·771	·824	·875	·925	·976	1·029	1·131	1·235
	25	·771	·835	·900	·964	1·028	1·093	1·156	1·221	1·285	1·415	1·513

—		£130	£140	£150	£200	£250	£300	£350	£400	£450	£500
Percentage allowed for interest and depreciation per annum.	5	·334	·360	·385	·514	·643	·772	·900	1·029	1·157	1·286
	7½	·501	·540	·579	·771	·964	1·157	1·350	1·543	1·736	1·929
	10	·668	·720	·770	1·029	1·286	1·543	1·800	2·057	2·315	2·571
	12½	·835	·900	·964	1·285	1·607	1·929	2·250	2·572	2·893	3·205
	15	1·003	1·080	1·155	1·543	1·928	2·314	2·700	3·086	3·471	3·857
	20	1·336	1·440	1·540	2·056	2·571	3·089	3·600	4·115	4·629	5·144
	25	1·671	1·800	1·925	2·572	3·125	3·857	4·500	5·143	5·786	6·430

Table V.—*Section per Thousand Amperes in Inches.*

Annual Cost of Electrical Horse-power.	1	1·1	1·2	1·3	1·4	1·5	1·6	1·7	1·8	1·9	2
£											
5	1·628	1·356	1·147	·980	·857	·746	·658	·585	·523	·471	·426
6	1·951	1·627	1·377	1·176	1·028	·895	·790	·702	·628	·565	·511
7	2·279	1·898	1·606	1·372	1·199	1·044	·921	·819	·733	·660	·595
8	2·605	2·169	1·838	1·568	1·370	1·194	1·053	·936	·838	·754	·682
9	2·930	2·441	2·065	1·764	1·542	1·343	1·185	1·053	·942	·848	·767
10	3·255	2·712	2·295	1·960	1·713	1·492	1·316	1·170	1·047	·942	·852
11		2·983	2·524	2·156	1·885	1·641	1·448	1·287	1·152	1·037	·937
12			2 754	2·352	2·056	1·790	1·580	1·404	1·256	1·131	1·022
13				2·548	2·227	1 910	1·711	1·521	1·361	1·225	1·108
14					2·398	2·089	1·843	1·638	1·466	1·319	1·193
15						2·238	1·975	1·755	1·570	1·414	1·278
16							2·106	1·872	1·675	1·508	1·363
17								1·990	1·780	1·602	1·448
18									1·884	1·696	1 534
19										1·790	1·619
20											1·704

Annual Cost of Electrical Horse-power.	2·1	2·2	2·3	2·4	2·5	2·6	2·7	2·8	2·9	3·0	3·1	3·2
£												
5	·383	·355	·324	·298	·276	·255	·237	·221	·206	·192	·180	·170
6	·463	·426	·389	·358	·331	·305	·284	·265	·247	·230	·216	·203
7	·540	·498.	·454	·417	·386	·356	·331	·309	·288	·269	·252	·237
8	·618	·569	·518	·477	·442	·407	·378	·353	·329	·307	·288	·271
9	·695	·640	·583	536	·497	·458	·426	·397	·370	·346	·324	·305
10	·772	·711	·648	·596	·552	·509	·473	·441	·411	·384	·360	·339
11	·849	·782	·712	·654	·607	·560	·520	·485	·452	·422	·396	·373
12	·926	·853	·778	715	·602	·611	·568	·529	·493	·461	·432	·407
13	1·004	·924	·812	·775	·718	·662	·615	·573	·534	·499	·468	·440
14	1·081	·995	·907	·834	·773	·713	·662	·617	·575	·538	·504	·475
15	1·158	1·066	·972	·894	·828	·764	·710	·662	·617	·576	·540	·509
16	1·235	1·137	1·037	·954	·883	·814	·757	·706	·658	·614	·576	·542
17	1·312	1·208	1·102	1·013	·938	·865	·804	·750	·699	·653	·612	·576
18	1·390	1·279	1·166	1·073	·994	·916	·851	·794	·740	·691	·648	·610
19	1·467	1·351	1·231	1·132	1·049	·967	·899	·838	·781	·730	·684	·644
20	1·544	1·423	1·293	1·192	1·104	1·018	·946	·882	·852	·768	·720	·678

Annual Cost of Electrical Horse-power.	3·3	3·4	3·5	3·6	3·7	3·8	3·9	4	4·5	5·0	5·5	6·0
£												
5	·160	·150										
6	·192	·180	·170									
7	·224	·210	·199	·188								
8	·256	·240	·227	·215	·203							
9	·288	·270	·255	·242	·229	·217						
10	·320	·300	·284	·269	·251	·241	·229					
11	·352	·330	·312	·296	·279	·265	·252	·240				
12	·384	·360	·341	·323	·305	·289	·275	·262	·206			
13	·416	·390	·369	·350	·330	·313	·298	·283	·224	·181		
14	·448	·420	·398	·379	·356	·337	·321	·305	·241	·195	·162	
15	·480	·450	·426	·404	·381	·362	·344	·327	·258	·209	·174	·147
16	·512	·480	·454	·430	·406	·386	·366	·349	·275	·223	·186	·156
17	·544	·510	·483	·457	·432	·410	·389	·371	·292	·237	·199	·166
18	·576	·540	·511	·484	·457	·434	·412	·392	·310	·251	·209	·176
19	·608	·570	·540	·511	·483	·458	·435	·414	·327	·265	·220	·186
20	·640	·600	·568	·538	·508	·482	·458	·436	·344	·279	·232	·196

thousand amperes, and this gives an area of 0·26 square inches for 100 amperes. It must be remembered that the annual cost of an electrical horse-power is to be determined by multiplying its average cost per hour by the total number of hours in the year during which the plant is at work; and that the current for which the proper area is found is not necessarily the maximum current, but is what we have called the equivalent current; that is, the current which, if maintained constant during all the working hours, would waste the same amount of energy in the year as is wasted by the varying currents actually carried by the conductor.

The maximum annual cost of an electrical horse-power given in the table, viz., £20, is much lower than the actual cost which is likely to occur in any central station work where a continuous supply is maintained; but the tables may still be used by means of the following expedient. Suppose the cost per horse-power is n times any one of the figures given, then we proceed as before to find from Table IV. the number, which is in the vertical column under the determined cost of laying one additional ton of copper, and in the same horizontal row as the percentage rate to be allowed. We then divide this number by n, and look along the horizontal row in Table V. opposite that figure which is equal to $\frac{1}{n}$th of our annual cost per horse-power, till we find the nearest number:—for example, suppose we again take £200 and 10 per cent. as the cost of laying the copper, and the rate for interest and depreciation; but that we take £54 as the annual cost of an electrical horse-power (this being about equal to a cost of 2*d*. per Board of Trade unit). We should again find the number 1·029 in Table IV.

and we may divide this by 3 and look opposite £18 per horse-power for the number 0·343. In this case we should find the nearest number was in the column headed 4·5 square inches, and by taking the proportional parts we should find that the most economical area per 1,000 amperes was about 4·3 square inches.

The problem solved by Lord Kelvin supposed that the current was the known quantity and the area of the conductor the unknown; but the converse case may present itself, and it may be necessary to determine the most economical current for a conductor which is already laid. In this case the annual charge for interest and depreciation is fixed, and the total annual charge against the conductor will therefore be a minimum when the energy wasted is a minimum; *i.e.* when no current is passing.

It is, however, evident that there is no economy in letting the conductor lie idle, and we must therefore find some other way of expressing the condition of greatest economy. This condition is always fulfilled when the ratio of the total cost of delivering the energy transmitted by the conductor to the revenue earned by this energy is a minimum; and we must therefore find the current that makes this ratio as small as possible.

Let C = full load current

m = ratio of mean current to full load current

e = ratio of equivalent current to full load current

V = pressure at consumers' end of conductor

w' = total cost of delivering one watt hour exclusive of the charges on the conductor itself

P = selling price of one watt hour

and let t, w, A, p, k, l, a, B bear the same significations as before.

The total cost of delivering the energy to the cus-

tomers is the sum of the cost exclusive of the annual charge on the conductor, i.e. $VmCt \times w'$ and of the annual charge on the conductor, i.e. $pl\ (ka + B) + (eC)^2 t \frac{Al}{a} \times w$; and the revenue is $VmCt \times P$. We have therefore to find the minimum value of

$$U = \frac{VmCtw' + pl\ (ka + B) + (eC)^2 t \frac{Al}{a} w}{VmCtP}$$

when C is variable.

This is a minimum when $\frac{dU}{dC} = -\frac{pl\ (ka + B)}{VmtPC^2} + \frac{e^2 t \frac{Al}{a} w}{VmtP} = 0$ that is when $pl\ (ka + B) = (eC)^2 t \frac{Al}{a} w$ or $C = \sqrt{\frac{pa\ (ka + B)}{e^2 t A w}}$.

It will be noticed that this solution differs from that obtained when the area of conductor was the variable in that the annual cost of wasted energy, instead of being equal to the annual charge for interest and depreciation on that part only of the capital outlay which is proportional to the area of the conductor, must now be made equal to the charge for interest and depreciation on the total capital outlay.

Both the equations given above for expressing C and a in terms of one another show that the economical current density is independent of the length of the conductor; and they can therefore only be applied to the case of several feeders of different lengths leaving the generating station, on the assumption that it is possible to supply current at the station end to each feeder at the particular pressure required by it without the use of resistances or other energy-wasting apparatus. If, however, as is most often the case, all the feeders start from omnibus bars in the station, so

that there must be the same fall of pressure in each, or that any independent regulation of pressure must be effected by interposing resistance in the feeder circuits, it is evident that the most economical result will not be obtained by using the same current density for all the feeders, as this would necessitate the use of additional resistances absorbing energy in the circuits of all the feeders except the longest one. The best result will indeed be obtained when no added resistances are necessary—that is, when the areas of the conductors are such as will give the same fall of pressure in each feeder; and we have therefore to find what fall of pressure will give the most economical results for the set of feeders.

It is evident that the most economical result will be obtained for a set of feeders when the ratio of the sum of the costs for all the feeders to the sum of the revenues is a minimum—that is when

$$U = \frac{Vmtw' \Sigma(C) + pk\Sigma(la) + pB\Sigma(l) + e^2twA\Sigma\left(\frac{C^2l}{a}\right)}{VmtP\Sigma(C)}$$

is a minimum. Since the fall of pressure v is to have the same value for all the feeders 1, 2, 3 . . . n at full load $v = \frac{C_1Al_1}{a_1} = \frac{C_2Al_2}{a_2} = \ . \ . \ . \ = \frac{C_nAl_n}{a_n}$

If the current and length of each feeder are known, and the area unknown, we substitute for a in the above expression its value in terms of v, which gives us

$$U = \frac{w'}{P} + \frac{pB\Sigma(l)}{VmtP\Sigma(C)} + \frac{\frac{pkA}{v}\Sigma(Cl^2) + e^2twv\Sigma(C)}{VmtP\Sigma(C)}$$

whence $$\frac{dU}{dv} = \frac{-\frac{1}{v^2}pkA\Sigma(Cl^2) + e^2tw\Sigma(C)}{VmtP\Sigma(C)} = 0$$

or $$v = \sqrt{\frac{pkA\Sigma(Cl^2)}{e^2tw\Sigma(C)}}$$

If the area and length of each feeder are known, and the current unknown, we substitute for C its value in terms of v, which gives us

$$U = \frac{w'}{P} + \frac{pA\{k\Sigma(la) + B\Sigma(l)\}}{vVmtP\,\Sigma\left(\frac{a}{l}\right)} + \frac{e^2twv}{VmtP}$$

$$\text{whence } \frac{dU}{dv} = -\frac{1}{v^2}\,\frac{pA\{k\Sigma(la) + B\Sigma(l)\}}{VmtP\Sigma\left(\frac{a}{l}\right)} + \frac{e^2tw}{VmtP} = 0.$$

$$\text{or } \quad v = \sqrt{\frac{pA\ \{k\Sigma(la) + B\Sigma(l)\}}{e^2tw\Sigma\left(\frac{a}{l}\right)}}$$

The best value of v having been determined, the areas or currents for the several feeders can be determined from the equations $a = \frac{CAl}{v}$ and $C = \frac{va}{Al}$.

It will be noticed that when the best economy is obtained in the first case, there is again equality between the annual charges for wasted energy and those for interest and depreciation on that part of the capital outlay which varies with the sectional area, these charges being totalled up for all the feeders; and that the second case again differs from the first only in that interest and depreciation is counted on the whole, and not on a part of the capital outlay.

In all that precedes we have assumed that the current, although varying in value from one moment to another, is uniform at any instant throughout the length of the conductor, as in a feeder cable; but as this condition does not exist in distributing cables from which the consumers' service wires are branched, we must, before the equations given above can be applied to these latter, find a co-efficient e_1 such that a current e_1C, if uniform throughout the length of the conductor, would waste the same amount of energy as the

gradually diminishing current in the distributing cable. The value of this co-efficient e_1 depends on the position of, and current taken off by each service, and can only be accurately calculated when these data are known; but $e_1 = \cdot 6$ gives a very fair approximation in most cases where the services are fairly evenly distributed along the conductor and take off approximately equal amounts of current. If, however, there are one or more consumers taking currents very much greater than the average, a special calculation should be made by summing up the watts wasted in each section along which the current is uniform, and finding the value of e_1 which gives $e_1{}^2 C^2 (R_1 + R_2 + R_3 + \ldots + R_n) = C_1{}^2 R_1 + C_2{}^2 R_2 + C_3{}^2 R_3 + \ldots + C^2{}_n R_n)$

The fact that the equivalent uniform current in a distributing cable may be a very small fraction of the full load current often makes it necessary to use an area of conductor which is larger than the most economical one as calculated by the rules given above; because this latter is too small to carry the maximum current without an undue rise of temperature: and the extra expense of arranging feeding points sufficiently close together to keep the fall of pressure in the distributors at full load within the prescribed limits may also lead to the same result.

We have already seen that the best economy is not obtained for a set of feeders by working at the same current density in all of them; and, for similar reasons, it is necessary to consider feeders and distributors together in order to arrive at the best results, which may require altogether different current densities in the two classes of main. The fall of pressure in the distributors being fixed, the maximum distance between feeding points is fixed for any given current density; and the extra cost of copper in the dis-

tributors, due to using a smaller current density than that indicated by the formulæ already given, may in many cases be more than counterbalanced by the saving due to the decrease in the number of feeders which results from the greater distance between feeding points.

Let us suppose that a feeder, of length L yards and area a square inches, supplies current to a distributor of area a_1 square inches, that the maximum current required is at the rate of α amperes per yard of distributor, that the fall of pressure in the distributor must not exceed v_1 volts at full load, and that it is required to find the length $2L_1$ of this distributor that can be most economically supplied by the feeder. The maximum current in the feeder will be $2\alpha L_1$ amperes, that in the distributor, which extends equally on both sides of the feeding point, will be αL_1, and the average watts delivered to consumers will be $2Vm\alpha L_1$.

Using the same symbols as before, the revenue will be $2Vm\alpha L_1 tP$, and the cost of delivering the electricity to the consumers will be $2Vm\alpha L_1 tw'$ plus the annual charge on the feeder $(2e\alpha L_1)^2 tw\frac{2AL}{a} + 2pL\,(ka + B)$ plus the annual charge on the distributor, which is—

$$2\left\{(ee_1\alpha L_1)^2 tw\frac{2AL_1}{a_1} + 2pL_1(ka_1 + B)\right\}$$

The current density at full load in the feeder is $D = \frac{2\alpha L_1}{a}$, so that $a = \frac{2\alpha L_1}{D}$. The fall of pressure at full load in the distributor is the product of the resistance of two yards of conductor into the sum of the currents in each yard of main; *i.e.*—

$v_1 = \frac{2\alpha A}{a_1}\left(1 + 2 + 3 + \ \ldots \ + L_1\right) = \frac{\alpha AL_1(L_1 + 1)}{a_1}$, which, when L_1 is large compared with unity, may be written

$v_1 = \frac{a\mathrm{AL}_1^2}{a_1}$ or $a_1 = \frac{a\mathrm{AL}_1^2}{v_1}$. Substituting for a and a_1 the values given above, we get for the ratio of cost to revenue—

$$\mathrm{U} = \frac{w'}{\mathrm{P}} + \frac{1}{\mathrm{V}mat\mathrm{P}}\left\{2e^2a\mathrm{D}tw\mathrm{AL} + \frac{2pka\mathrm{L}}{\mathrm{D}} + \frac{p\mathrm{LB}}{\mathrm{L}_1} + 2e^2e_1^2atwv_1 + \frac{2pka\mathrm{AL}_1^2}{v_1} + 2p\mathrm{B}\right\},$$ and $$\frac{d\mathrm{U}}{d\mathrm{L}_1} = -\frac{p\mathrm{LB}}{\mathrm{L}_1^2} + \frac{4pka\mathrm{AL}_1}{v_1} = 0,$$

or the ratio of cost to revenue is a minimum when—

$$\mathrm{L}_1 = \sqrt[3]{\frac{\mathrm{B}v_1\mathrm{L}}{4ka\mathrm{A}}}, \text{ and } a_1 = \sqrt[3]{\frac{a\mathrm{AB}^2\mathrm{L}^2}{16k^2v_1}}.$$

In calculating a network of conductors, one should first determine the best position for feeding points, and then calculate the areas of the distributors so that the fall of pressure does not exceed the fixed limit, and the areas of the feeders so that the fall of pressure in them shall be that which gives the best result for the set. To follow this method exactly would probably lead to the use of a large number of conductors of sectional areas not included in the standard lists of cable makers, and to avoid this inconvenience it is usual to fix on certain areas which may be employed, and to arrange the network so that the best results may be obtained under these conditions.

In such a case, when the values of B, k and v_1 have been fixed, it is useful to prepare a table giving the values of L and L_1 for each area of conductor that may be used with different values of a. This can be done from the equations given above for the value of a_1, from which we get $\mathrm{L}_1 = \sqrt{\frac{a_1v_1}{a\mathrm{A}}}$ and $\mathrm{L} = \frac{4k}{\mathrm{B}}\sqrt{\frac{a_1^3v_1}{a\mathrm{A}}}$, all the terms on the right hand side in both equations being constant except only a_1 and a.

To show more clearly the method of procedure, let

us take, as an example, a ring main ABCD, of which the sides AB and CD are each 2,000 yards long, and BC and AD are each 1,500 yards long; let the average current required per yard of main be $a=1$ in AD, $a=\cdot 5$ in AB and CD, and $a=\cdot 25$ in BC; let the generating station be at O, 800 yards from AD, and 700 yards from AB, and let us suppose that the feeders can only be run in streets parallel either with AB or AD.

Assume the following values for the constants which will be necessary in the calculations:—

$$
\begin{aligned}
v_1 &= 12\\
B &= 0\cdot 25\\
k &= 0\cdot 775\\
p &= 0\cdot 1\\
t &= 8760\\
w &= 5 \times 10^{-6}\\
e &= 0\cdot 262\\
A &= 25\cdot 5 \times 10^{-6}
\end{aligned}
$$

and let us suppose that we may use any conductors of which the area is a multiple of $\frac{1}{20}$th of an inch.

The following table shows the values of L and L_1 for different values of a_1:—

TABLE VI.

a_1	$a=1.$		$a=0\cdot 5.$		$a=0\cdot 25.$	
	L	L_1	L	L_1	L	L_1
0·15	494	266	698	376	988	532
0·20	761	306	1076	433	1522	613
0·25	1063	343	1503	485	2126	686
0·30	1398	376	1976	531	2796	752
0·35	1762	406	2491	574	3524	812

The maximum current being numerically equal to L_1, when $a=1$ it will be noticed that the current densities

are such as probably could not be allowed when the heating of the conductor is taken into consideration, and we will suppose that the maximum current must never give a density of more than 1,200 amperes per square inch, so that with the exception of the ·35

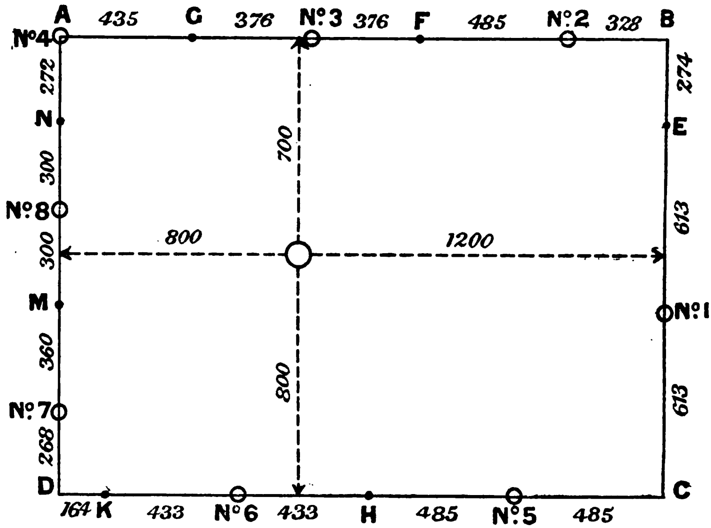

FIG. 5.

square inch cable the values of L_1 must be taken as $1{,}200a_1$ when $a=1$. We will now settle the position of the feeding points with the assistance of the above table; but before doing so we would point out that in any actual case there are other considerations that must not be neglected, such as the greater convenience of certain positions over others as feeding centres; and in such cases the practical experience of

the engineer must decide to what extent it is advisable to depart from the results found by calculation.

Let us start from C as the neutral point between two feeder systems, and determine the point for No. 1 feeder in BC. We have $L + L_1 = 2000$, that being the distance from O to C, and referring to the table under $a = \cdot 25$, we see that a cable of $\cdot 20$ square inches most nearly gives the desired value of $L + L_1$. We therefore fix No. 1 at 613 yards from C, and we have $L_1 = 613$, $L = 1387$, the current in the feeder $= C_1 = 306 \cdot 5$, EC $= 1226$, whence BE $= 274$.

A reference to the table will show that feeding point No. 2 will fall in AB, say l yards beyond B, and as the value of a changes at B, we must find a length L_1, which with $a = \cdot 5$ will give the same fall of pressure as l yards with $a = \cdot 5$, and 274 yards with $a = \cdot 25$. The fall of pressure in EB is equal to $\frac{\cdot 25 A (274)^2}{a_1}$, and the current at B is $\frac{274}{4}$ amperes, whilst the fall of pressure in the l yards from No. 2 to B equals $\left(\frac{274}{4} \times \frac{2lA}{a_1}\right)$ $+ \frac{\cdot 5 A l^2}{a_1}$; and $v_1 = \frac{\cdot 5 A L_1^2}{a_1} = \frac{A}{2a_1}\left\{l^2 + 274 l + \frac{(274)^2}{2}\right\}$, or $L_1^2 = l^2 + 274 l + \frac{(274)^2}{2}$. From this equation we can see at once that $L_1 - l$ has a value between 137 and $\frac{274}{\sqrt{2}} = 194$, and since $L + l = 1900$, $L + L_1$ should be, if possible, between 2037 and 2094. An area of $\cdot 25$ giving $L_1 = 485$ is the nearest, and substituting this value of L_1 in the equation connecting L_1 and l, we find that $l = 328$, so that No. 2 is 328 yards from B, whence $L = 1572$, BF $= 485 + 328 = 813$, and $C_2 = 475$.

For No. 3, $L + L_1 = 1900 - BF = 1{,}087$, whence $a_1 = \cdot 15$, $L_1 = 376$, $L = 711$, $FG = 752$, $AG = 435$, and $C_3 = 376$.

For No. 4, $L - L_1 = 1065$, whence $a_1 = \cdot 25$, $L_1 = 485$, which would place No. 4 50 yards beyond A where a changes from ·5 to 1. Before settling the exact position of No. 4, we may start again from C along CD, and fix the other feeding points.

For No. 5, $L + L_1 = 2000$, whence $a_1 = \cdot 25$, $L_1 = 485$, $L = 1515$, $CH = 970$, $C_5 = 485$.

For No. 6, $L - L_1 = 800 - 230 = 570$, whence $a_1 = \cdot 20$, $L_1 = 433$, $L = 1003$, $HK = 866$, $DK = 164$, $C_6 = 433$.

For No. 7, which will fall in DA, say l yards beyond D, we must again take out the fall of pressure from D to K and from No. 7 to D, from which we find that $L_1^2 = l^2 + 164l + \frac{(164)^2}{2}$, whence $L + L_1 =$ about 1,700. This gives us $a_1 = \cdot 3$, $L_1 = 1200a_1 = 360$, $l = 268$, $L = 1600 - 268 = 1332$, $MD = 628$, and $C_7 = 710$.

For No. 8, $L - L_1 = 628$, for which we may take $a_1 = \cdot 25$, $L_1 = 300$, $L = 928$, $MN = 600$, $AN = 272$, and $C_8 = 600$.

Reverting now to No. 4, if we fix it at A, we could with $a_1 = \cdot 25$ go 485 yards in AB and 300 yards in AD, whilst the actual distances are 435 yards in AB and 272 yards in AD, so that the position mentioned is as good as any that can be found. This gives us $L = 1500$, $C_4 = 489{\cdot}5$. As we have already mentioned, the feeding points fixed by the above method may not come in the most convenient positions; and this and other reasons, such as the convenience of having the same area of cable throughout between two adjacent feeding points, may lead the engineer to modify the positions as found by the above method. We will, however, suppose that the feeding points remain as shown above, and will proceed to find the areas of the feeders themselves, for which we first determine the

most economical fall of pressure in the feeders by the equation $v=\sqrt{\frac{pkA\Sigma(Cl^2)}{e^2tw\Sigma(C)}}$, which, since $l=2L$, may be written $v=\sqrt{\frac{4pkA\Sigma(CL^2)}{e^2tw\Sigma(C)}}$, whence $v=65{\cdot}8$.

The area of each feeder can now be calculated from the equation $a=\frac{2ALC}{v}$, and the results tabulated.

TABLE VII.

Feeder.	L.	C.	Calculated Area.	Actual Area Used.
No. 1.	1387	306·5	·330	·350
„ 2.	1572	475	·579	·600
„ 3.	711	376	·207	·300
„ 4.	1500	489·5	·569	·600
„ 5.	1515	485	·570	·600
„ 6.	1003	433	·337	·350
„ 7.	1332	710	·733	·750
„ 8.	923	600	·432	·500

The areas, as calculated, are given in the fourth column, and in the fifth column are given the areas which, being multiples of $\frac{1}{20}$th inch, can be employed; the nearest area larger than the calculated one being taken in all cases, except for feeders 3 and 8, when a further increase has been made, so that the current density may not be so great as to cause undue heating.

CHAPTER IV.

Systems of Distribution.—Series System.—Parallel System.—Feeders.—Combinations of Series and Parallel Systems.—Three-Wire System.—Accumulators as Equalizers.—Multiple Wire Systems.—Transformer Systems.—Motor-generators.—Accumulators.—Alternating Current Transformers.

THE choice of the system of distribution, which will be best suited to the requirements of any particular installation, is a matter which requires the most careful consideration; and although cases may occur where there is no question as to which system is most economical, yet in a general way this is not so; and we find that there are very great differences of opinion amongst engineers, and that a great deal may be said in favour of each of the rival systems that are in use at the present time. No matter what system is employed, the prime object of all must be the same, viz., to distribute the current from the terminals of the dynamo machines to the various places where it is to be used, for lighting or other purposes, with the smallest possible loss of energy and the smallest expenditure of capital; but in addition to this, there are other questions, such as convenience of regulation, and possible risks of breakdowns, which have to be considered; and the relative values assigned to these points, as factors in the determination of the choice of a system, vary very much.

If we consider only the conductor itself, we see at once that we can reduce the capital expenditure on, and the annual waste of energy in it by increasing the pressure; since with the same output an increased pressure allows of the use of a smaller current, which

can be carried by a smaller conductor, and at the same current density will cause less heating, and give a smaller percentage drop of pressure over any given length. This gain, however, is to a certain extent counterbalanced by the fact that the insulation of the conductor becomes more costly, and that in most cases the high pressures entail the use of special apparatus to reduce the pressure of supply before the current can be used by the consumer.

With few exceptions, the conditions of supply are such that either the pressure or the current must be maintained constant; for instance, when the current is to be used for lighting purposes, each individual lamp will require a definite pressure and current, and

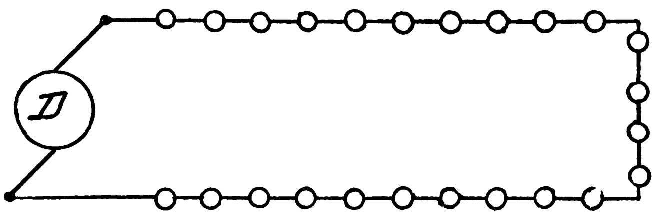

FIG. 6.

the lamps may be so arranged that the same current shall flow through each, and that the pressure shall be varied according to the number of lamps in use; or, on the other hand, they may be connected up so that the pressure may be maintained constant and the current varied according to the number of lamps in use. The former is called the series system, and in it a conductor is led from one terminal of the dynamo to the first lamp, from it to the second lamp, and so on back to the other terminal of the dynamo, as shown in the accompanying Figure 6, where D is the dynamo machine and the circles represent the lamps; the

latter is called the parallel system (shown in Figure 7), and in it two conductors, each coupled to one terminal of the dynamo, are connected together by a number of branches in each of which may be placed a lamp.

At first sight it would appear that the series system must necessarily be the better of the two, since the pressure that can be used for lighting on the parallel system is limited by the maximum pressure for which an incandescent lamp can be made, and at present this is little more than 200 volts; whereas the pressure that can be used with the series system is only limited by difficulties of insulation in the dynamo

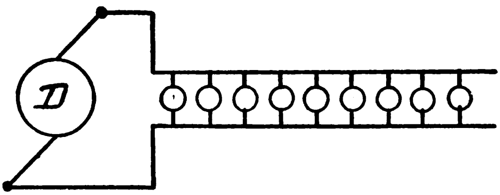

FIG. 7.

machine and conductors, and in the case of direct current dynamos, by the difficulties of collecting the current. It is this last which really fixes the limit, but even with closed circuit dynamos the pressure may be as high as 1,500 to 2,000 volts; and with open circuit dynamos, such as are mostly used for arc lighting, it may be as high as 3,000 or 4,000 volts. It is evident that a great saving may be made in the weight of copper in the conductors by the use of such high pressures; and further, the series system has this great advantage, that the fall of pressure along the conductor does not in any way affect the illuminating power of the lamp, since this latter will burn at full power so long as the current is maintained constant.

The advantages of the series system of distribution are, therefore, that smaller conductors can be used, and that the distance from the nearest to the farthest lamp may be made very great without affecting the illuminating power. The disadvantages are, that the high pressure is carried all over the consumer's premises, and that therefore the dangers arising from an accidental contact with the conductors are increased; that the rupture of the circuit in any one place will stop the flow of current entirely, and that therefore special arrangements of a more or less complicated nature have to be made to prevent this happening when a lamp filament breaks, or an arc lamp does not feed properly; and lastly, that an absolute limit is put to the number of lamps that can be operated from one dynamo, by the fact that an incandescent lamp of the usual candle-power cannot at present be made to work with a lower pressure than about 6 volts. The conditions which are most favourable to the use of the series system are those which occur in street lighting, where the lamps are placed at regular intervals along the streets, and the distance of the farthest lamp from the dynamo and of each lamp from its neighbour is considerable. Under such conditions the use of the simple parallel system is practically impossible, since the weight of copper which would be necessary in the conductors, to keep the variation of pressure within fair working limits, is prohibitory.

With regard to the economy in conductors, one point should be noticed, which diminishes the advantages of the series system when employed for general distribution where the load varies much; and that is, that the waste of energy in the conductor is the same whether the full load or only 1 per cent of it is on; whereas in a parallel system the waste energy decreases even

more rapidly than the load. In calculating the economical size of conductor we must, therefore, for a series system take the full value of the current as the equivalent current, whilst in a parallel system, according to published data, the equivalent current is often only 20 to 25 per cent of the maximum; and from this it follows that, for the same area of conductor with equal annual waste of energy, the series system must, for similar conditions of supply, work with a pressure higher than that of the parallel system in the ratio of 100 to 20 or 25. On the other hand, however, the engines at the station will be working more economically at light loads than they would in a parallel system, since in a series system a reduction in load may be accompanied by a reduction in speed of the generating plant, whilst the mean effective pressure in the cylinder and therefore the efficiency per stroke is maintained the same.

In the parallel system of distribution, the pressure should be kept constant at the terminals of all the lamps; and herein lies one of the greatest difficulties which have to be overcome in this system, because absolutely constant pressure can only be maintained when either no current is flowing or the conductors are of infinitely large area. Whenever a current is flowing through a conductor which offers some resistance to it, there is a fall of pressure, which, as has already been shown, varies in proportion to the current density and to the length of the conductor; and as the current density should be fixed by the economical laws discussed in Chap. III., the fall of pressure may be said to depend only upon the length of the conductor. In practice a variation of pressure of about 4 or 5 per cent. at the lamp terminals is the maximum allowable; but, in a system of distribution from a

central station, only a part of this must be in the distributing conductors, since allowance has to be made for the housewiring, with the result that the maximum variation at the house terminals should not exceed $2\frac{1}{2}$ to 3 per cent. The pressure of supply being limited to 200 volts, or thereabouts in the simple parallel system, on account of the difficulties of obtaining satisfactory incandescent lamps for higher pressures, this fall of $2\frac{1}{2}$ to 3 per cent. means a maximum fall of 5 to 6 volts; and therefore the greatest distance between the lamps nearest to and farthest from the dynamo must be small, unless conductors are used of much larger areas than those which are dictated by economy. The actual distances may be calculated from the equation $V = \frac{25{\cdot}5D(L+1)}{10^6}$ where V = fall of pressure in volts, D = the current density per square inch, and L = the distance in yards. If we take V as 6 volts, this may be written $L = \frac{6 \times 10^6}{25{\cdot}5D} - 1 = \frac{235300}{D} - 1$ which shows that, for a maximum current density of 1,000 amperes per square inch, the greatest distance between the lamps must not exceed 235 yards; at 800 amperes per square inch L becomes 293 yards; at 600 amperes per square inch 391 yards, and so on.

The great disadvantage of the simple parallel system is then that the cost of the conductors practically becomes prohibitive when an extended area has to be dealt with; but, on the other hand, the requirements in the way of insulation are comparatively easy to fulfil, there is no chance of receiving dangerous shocks, and the arrangement of the conductors is extremely simple; so that this system is universally employed for all small installations, and has also been used to a great extent for central station work, with the addition

of feeding mains such as were mentioned in a preceding chapter. These feeding mains or feeders (Fig. 8) are conductors, by means of which a number of points like A or B in the district to be lighted are connected to the dynamos, and off which no branches are taken

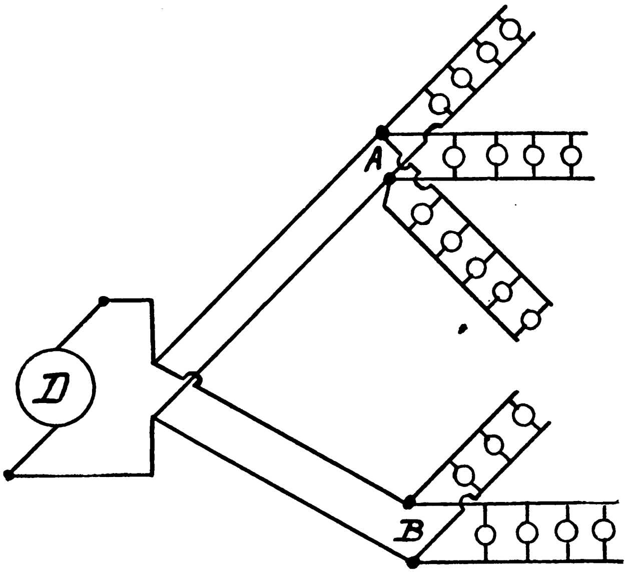

FIG. 8.

except at these points. Under these circumstances, each of these points may be considered as the centre of a supply, and as replacing a dynamo machine fixed at the end of the feeder, if arrangements are made for maintaining the pressure at each point at a constant value by varying it at the terminals of the dynamo machine.

The pressure at the distributing points may be measured by running back pressure wires from each of them to the station, so that an ordinary voltmeter in the latter place will register the pressure at the far end of the feeder; or by using a compensated voltmeter, that is, one so arranged that a coil carrying the main current, or a portion of it, acts in opposition to the voltmeter coil proper; this main current coil being so adjusted that it always balances the effect of the extra pressure due to the current flowing in the feeder, and so causes the instrument to register the pressure at the distributing point. In either case the reading of the voltmeter is kept constant by varying the pressure at the terminals of the dynamo, or by putting in or taking out resistances in the feeder circuit. It will be seen, therefore, that by a liberal use of feeders, the difficulties of variation of pressure at the lamps may be entirely got over; but, although the fall in the feeders need in no way affect the pressure at the lamps, the waste of energy which results from it, and the great size of the conductors in the simple parallel system, are both items of considerable importance in the cost; and although the recent improvements in the production of lamps to work at 200 to 230 volts now permit of the use of the simple two-wire system for much larger areas than was possible a short while ago, yet in extended systems it is found necessary to still further raise the pressure of supply.

To reduce the outlay on the conductors and the waste of energy in them, several combinations of the series and parallel systems have been proposed and used; such as the running of groups of incandescent lamps on a series circuit, the lamps in each group being in parallel; and the placing of two or more lamps in

series in each of the branches of a parallel system. The former system, represented diagramatically by Fig. 9, has been employed chiefly for the purpose of running incandescent lamps on a series arc lighting circuit; whilst the latter, which is shown in Fig. 10, has

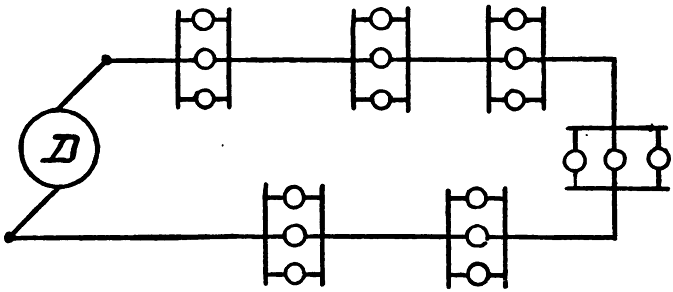

FIG. 9.

chiefly been used when lamps of small candle-power, which can only be made for pressures of say 25 to 30 volts, have been employed. In neither case are the individual lamps independent, but each group must be considered as though it were one lamp; and, for this

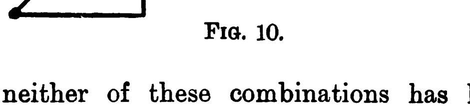

FIG. 10.

reason, neither of these combinations has had any very extended use, being decidedly unsuitable for the purposes of a public supply.

A modification of the second system, which was

first introduced by Edison in America, and by Hopkinson in England, has however met with general favour; since with the higher pressure are retained in great measure the advantages of easy manipulation which are found in the simple parallel system. This three-wire system differs from the one shown in Fig. 10 by having a third wire to which all the middle terminals of the lamps are connected, and by employing two separate dynamo machines connected in series

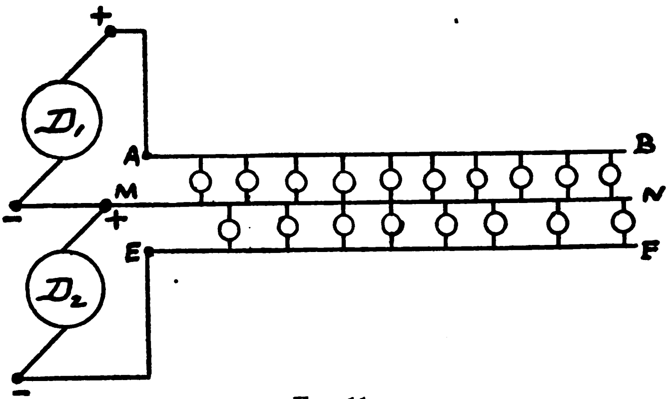

FIG. 11.

with one another. Fig. 11 shows the arrangement of the dynamos, conductors, and lamps; from which it will be seen that each dynamo may be considered to have an independent circuit completed by one of the outer conductors, the middle conductor, and the group of lamps connected to them. Taking the dynamo D_1, the current flows from it along the outer conductor towards B, through the lamps connected between AB and MN, and along the middle conductor to the negative terminal of the dynamo. The current from D_2 flows along the middle conductor

towards N, through the lamps between MN and EF, and along the outer conductor from F to the negative terminal of the dynamo. If the currents required for the two groups of lamps are equal, it is evident that no current can flow along MN; but that it will flow from the positive terminal of D_1 along AB, through the two sets of lamps, and will return along FE to the negative terminal of D_2. But if the currents are unequal, then a current of C_1 amperes will leave the positive terminal of D_1 and flow through the upper set of lamps to the middle conductor; there it will divide, a current of say C_2 amperes flowing through the lower set of lamps to the negative terminal of D_2, and a current of $C_1 - C_2$ amperes flowing along the middle conductor to the negative terminal of D_1; that is to say, each dynamo will supply just the proper amount of current for its own group of lamps, the current in each outer conductor will be that required for the group of lamps connected to it, and the current in the middle conductor will vary in strength and direction according to the relative values of C_1 and C_2, being numerically equal to the difference of C_1 and C_2, and in the same direction as the smaller current of the two. In practice the difference in the values of C_1 and C_2 on a circuit supplying a large number of lamps is found not to be more at any time than half the maximum current, and generally it is much less, so that the area of the middle conductor need not be more than half that of either of the outside conductors.

With this system, since the pressure is doubled, the current required to supply the same number of lamps is only half that with the two-wire system; and therefore, at the same current density, the area of each outside conductor is one-half, and of the middle conductor one-quarter of the area of either conductor in the two-wire

system; giving, for equal lengths, a ratio of total weights of copper in the proportion of 5 : 8; for example, suppose 800 amperes requiring one square inch of copper is the current for the two-wire system, then the combined area of the conductors will be two square inches; whilst, in the three-wire system, the current will be 400 amperes, the area of each outside conductor one half square inch, and that of the middle conductor one quarter square inch, which gives one and a quarter square inches for the combined area. The fall of pressure per yard of conductor would be exactly the same in the two systems; but, since the working pressure in the three-wire is twice that in the two-wire system, the length of conductor which will give the same percentage fall is doubled, and the figures given on page 63 for the maximum distance between lamps for a 3 per cent. fall may, therefore, be increased to 470 yards for a current density of 1000 amperes per square inch, 586 yards for 800 amperes per square inch, 782 yards for 600 amperes per square inch, and so on. These distances are still much too short for the requirements of most districts, so that the use of feeders is equally necessary with the three-wire as with the two-wire system; but the distributing points may now be placed at twice the distance from one another, and the number of feeders may therefore be considerably decreased.

A modification of this system is sometimes employed, which dispenses with the third wire in the feeding mains, and permits of the use of one dynamo supplying current at, say 200 volts, instead of two dynamos each supplying current at 100 volts. Fig 12 shows the arrangement of the apparatus in which D is the dynamo supplying current at 200 volts, which is conveyed by a two-wire feeder main to the distributing point A, at which is placed a battery of accumulators;

and to the two outside terminals and the middle terminal of this battery, the three distributing wires are connected. The accumulators here play the same part as their namesakes do in a system of hydraulic supply; the half battery connected to the circuit which requires most current discharges into that circuit, and so helps the dynamo machine; and the half battery, connected to the circuit in which the demand is smaller, is charged by the surplus current. Thus, suppose that the two circuits require currents of C_1 and C_2 amperes

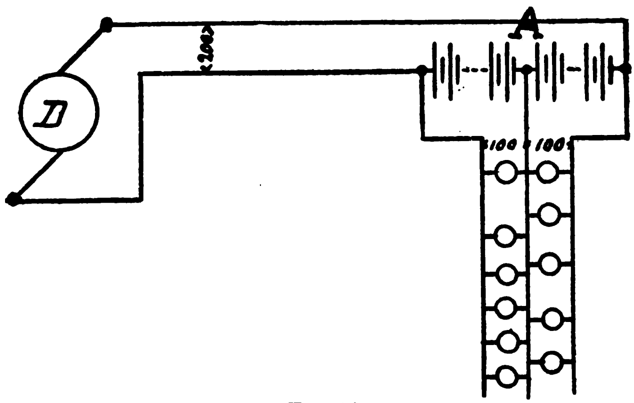

FIG. 12.

respectively, the dynamo will supply a current of about $\frac{C_1 + C_2}{2}$, and one-half battery will supply about $\frac{C_1 - C_2}{2}$ amperes, thereby making the total in its circuit $\frac{2C_1 + C_2 - C_2}{2} = C_1$ amperes; whilst the other half battery will be charged at the rate of $\frac{C_1 - C_2}{2}$ amperes, so that the current in the smaller circuit will be reduced to $\frac{C_1 + C_2 - (C_1 - C_2)}{2} = C_2$ amperes.

So far as first cost is concerned, there is no saving effected by this arrangement; since the cost of batteries at the distributing points more than counterbalances any saving due to there being no middle wire, and only one dynamo instead of two of half the output; but the batteries are able, during the hours of small demand, to supply all the current required without the aid of the dynamo machines, and consequently a saving in engine-room expenses may be made by stopping the running machinery altogether for some hours in each day. As a set-off against this, there is the cost of upkeep of the accumulators and their regulating gear, and of the loss of energy in the accumulators themselves, and this naturally depends on the merits of the particular type of accumulators employed.

Another modification which is sometimes used with a view to reducing the first cost is to do away with the third wire for each separate feeder, and to connect the third wire of the distributing mains by one or more conductors to the station; for example, if we suppose that there are six feeders, we may, instead of laying a third wire for each, replace these six conductors by two or three, directly connecting the middle terminal at the station to the middle wire of the distributing network at two or three points; the idea being that the inequalities in the demand for current on the two sides of the three-wire system are local, and that they will to a great extent counterbalance one another, so that the total want of balance on the whole system will be small.

The multiple-wire system, of which the three-wire system is the simplest case, may be extended so as to permit of the use of still higher pressures; for instance, four wires may be used with a pressure equal to three times that at the lamp terminals, five wires with four

times, and so on. The practical disadvantages of the extension of the system in this manner are, that it gives rise to greater complication in the arrangement of the mains and of the regulating apparatus, and that the introduction of the higher pressures into the consumer's premises is objectionable. So long as the pressure at the lamp terminals was limited to 100

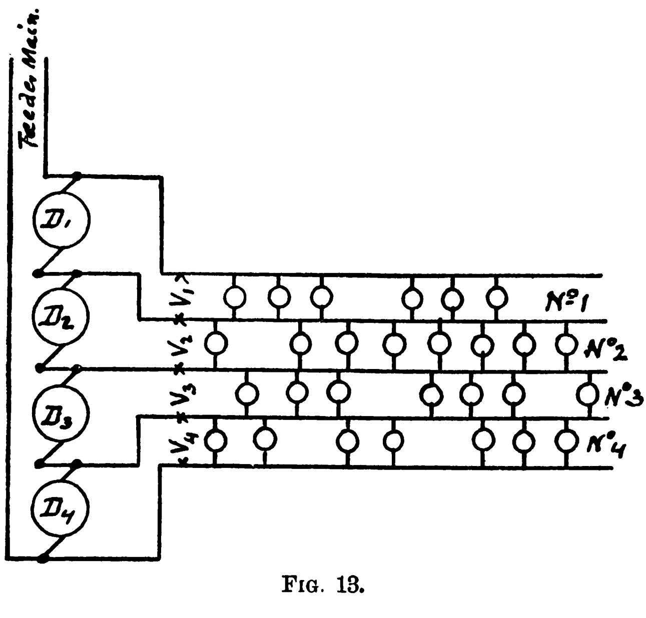

FIG. 13.

volts or thereabouts, a four or five-wire system was necessary, if a working pressure above 200 to 250 volts was required; and multiple-wire systems have been installed in several towns, as, for example, Manchester and Paris. Now, however, that a three-wire system can be worked at a pressure of 400 to 500 volts, which is as high a pressure as can be allowed with direct

supply, there is no advantage to be gained by the use of four or more wires, which can act as a set-off to the greater complication of such a system, and it is not therefore likely that more such installations will be laid down. Generally, when this system is in use, five wires are employed for distribution with two-wire feeders and pressure equalizers at the distributing points. The pressure equalizers are in some cases accumulators, four 100 volt batteries being connected in series across the ends of the feeder, with five distributing wires connected one to each of the two outside and three intermediate terminals; whilst in others the pressure is equalized by means of electro-dynamic machinery.

This latter method has been adopted in some cases in a system put down in Paris, the apparatus consisting of a quadruple dynamo machine, in which four armatures of very low resistance are mounted on one common shaft, and are connected together in series across the feeders. The two outside and three intermediate terminals of these armatures are connected one to each of the five distributing wires, as shown diagramatically in Fig. 13 (in which, for the sake of convenience, the four armatures are shown side by side instead of in line with one another). Each armature runs in a magnetic field of the same strength and direction; each has the same number of turns of wire on it, and all are obliged to turn at the same speed, being mounted on one shaft; therefore the difference of potential between the feeders will be equally divided between the four armatures, so long as the resistance in the four lamp circuits, each of which is connected as a shunt on one of the armatures, is equal. Under these circumstances, a small current only flows through the armatures, just sufficient to keep them running at normal speed against the load due to the friction of the bearings, and the

losses due to hysteresis and eddy currents in the armatures themselves. Suppose now that the number of lamps, and therefore the current, in circuit 1 is increased, and in circuit 2 is diminished; then, since the sum of the currents in each circuit and its corresponding armature must be the same for all of them, the current in number 1 armature must be diminished, and that in number 2 increased. The pressures V_1 and V_2 will tend to change in a similar manner, with the result that number 2 armature will tend to run faster, and number 1 to run slower. Since the two armatures are on the same shaft, and must therefore run at the same speed, number 2 will act as an electromotor, and give out power to drive number 1, which will become a generator and supply current. If the currents required in the lamp circuits are C_1, C_2, C_3, C_4, respectively, the current C supplied from the generating station will be equal to $\frac{C_1 + C_2 + C_3 + C_4}{4}$ plus a small amount which must be allowed for overcoming the losses in the regulator; and, if we suppose that C_1 and C_4 are greater, and that C_2 and C_3 are less than C, then the armatures 2 and 3 will run as motors, and receive currents equal to $C - C_2$ and $C - C_3$ respectively; and the armatures 1 and 4 will run as generators, and supply current to their circuits equal to $C_1 - C$ and $C_4 - C$ respectively. The pressures V_2 and V_3 will be greater than V_1 or V_4 by an amount depending on the currents in the corresponding armatures and on their conductor resistances; but this variation of pressure may be rendered very small by making the resistance of the armatures small also.

At Manchester a five-wire system has been installed, in which the five wires are brought into the station, and dynamos giving about 100 volts were provided for

compensating the inequalities of load on the four branches. These dynamos are now, however, rarely if ever used, the balancing being effected by motor-generators placed in sub-stations at various parts of the network, which is fed by two wire feeders supplied at about 400 volts. In each sub-station there are two motor-generators coupled together, the four armature circuits being connected respectively to the four branches of the five-wire distribution; the armature circuits connected to the branches where the demand for current is least act as motors and supply power to drive the combination and generate current in the armature circuits connected to the heavily loaded branches in the same way as in the case of the pressure equalizers used in the Paris installation.

If higher pressures than 400 to 500 volts are required, the direct system of supply has to be abandoned, and the current supplied from the station at a high pressure is delivered to a transforming apparatus which reduces the pressure to one suitable for the internal wiring of buildings.

This transforming apparatus contains two circuits insulated from one another, one of which is connected to the primary or supply mains, and the other to the secondary or house mains. It is this insulation of the supply mains from the house mains that is one great advantage of the transformer system, since it divides the house circuits up into sets, each of which contains a comparatively small number of lamps, and can therefore be arranged so that its general leakage is very small; and further, it can be so arranged that the maximum pressure between any two points in the secondary circuits need never be more than 100 volts, and may be less if desirable.

The name of transformer, when used without further

qualification, is generally applied to a modification of the induction coil, which is used with alternating currents; but motor-generators or accumulators may be used as transformers, when a continuous current is employed. The alternating current transformer consists of two coils of insulated wire interlinked with a magnetic circuit; one coil, being connected to the supply mains, is traversed by the alternating current generated by the dynamo machine; this alternating current produces reversals of magnetism in the magnetic circuit, which in turn induce an alternating current in the other coil which is connected to the secondary or lamp circuit. The motor-generator is a combination of two dynamo machines, one of which is supplied with current from the primary mains; and, acting as a motor, supplies the power necessary to drive the other, and cause it to generate a current of electricity. Two separate machines coupled together by mechanical gearing may be used for this purpose; but, in actual practice, one machine with two separate windings on its armature is generally employed. When accumulators are used as transformers, two independent batteries are arranged in such a manner that one is in the primary circuit being charged, whilst the other is connected in the secondary circuit and discharges through the lamps; this separation of the primary and secondary circuits being what constitutes the difference between the transformer and the regulator.

The primary circuits of these transformers may be coupled up in series or in parallel with one another, and the lamps in the secondary circuit may also be connected in either of these ways; but of the four possible combinations, one presents such difficulties in the matter of regulation that, for all practical purposes, three only need be considered. These are :—

(1) Transformers in series, lamps in series.
(2) Transformers in series, lamps in parallel.
(3) Transformers in parallel, lamps in parallel.

(1) This system has been proposed by Mr. Bernstein as a means of overcoming some of the difficulties which occur in the direct series system, viz., that the number of lamps on each circuit and also the unit generating plant must be inconveniently small, and that the high pressure must be introduced into the house circuits. He proposes to use a continuous current, and to fix a motor-generator in each house to be lighted, their primary circuits being connected in series, and carrying a current of 50 amperes or more, whilst their secondary circuits each supply current, say at 10 amperes, to groups of lamps arranged in series as shown in Fig. 14. By this means, the size of the unit generating plant and the number of lamps on each circuit may be increased five times, or more, for the same maximum pressure, which does away with the inconvenient multiplication of machines and circuits; but there is still the objection that, unless the output of the motor-generators is in all cases restricted to about 50 lamps of 16 candle-power, the pressure in the secondary or house circuit becomes higher than is convenient.

As regards the possible economy of the system, what has been already said about the direct series system holds good; viz., that an increased economy may be obtained in the generation of the current, but that the system of distribution, with such load factors as are generally found, is uneconomical. If we consider the working conditions, this will at once become evident; since, in addition to the interest and depreciation on, and the cost of the energy wasted in the conductors, we have here, as in all transformer systems, to include the same annual charges for the motor-generators.

Now each of these motor-generators must be able to supply current to all the lamps connected to it; whereas the maximum load on the circuit at any time may not exceed 60 per cent. of that required for all the lamps, and the average load may be only 20 per cent. of the maximum, or 12 per cent. of the added outputs of all

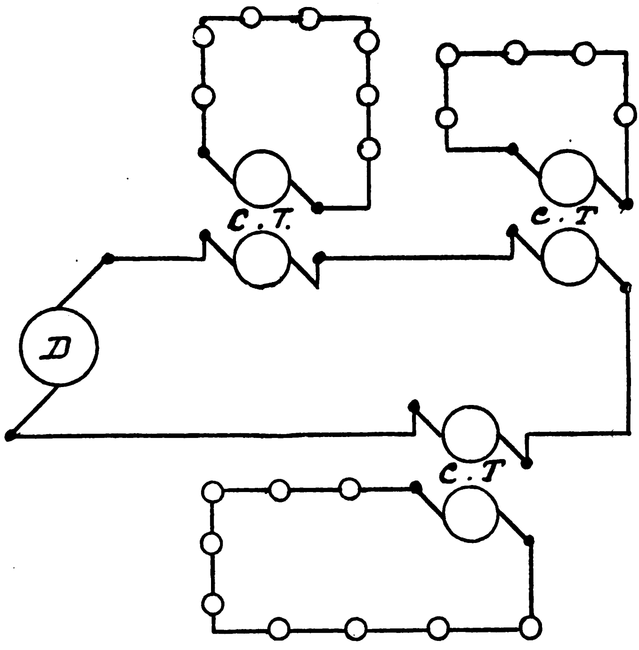

FIG. 14.

the transformers. If we allow an electrical efficiency of 90 per cent. for each motor-generator at full load, which is probably too high for such small machines, and a loss of about 3 per cent. in the mains, we get a total loss in the circuit equal to about 12 per cent. of the maximum output of the transformers, without con-

sidering the losses due to friction or heating of the armature cores. Now this waste goes on all the same whatever number of lamps is in use; and therefore, on an average load of 12 per cent. of the transformer capacity, that is 20 per cent. of the maximum load of the whole circuit, we find that we have to generate at least two units at the station for each one used in the lamps.

A similar system may be used with alternating currents for working incandescent or arc lamps, and it has

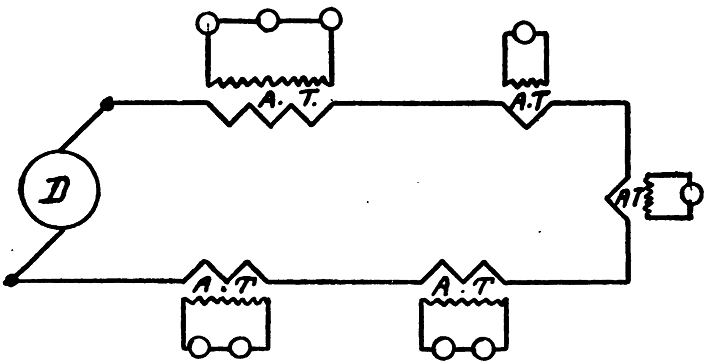

FIG. 15.

been adopted by the Westinghouse Co. in America, for both street and private lighting with arc lamps. The circuit is arranged as shown in Fig. 15, where D is the dynamo machine, and A.T., A.T., . . . are transformers serving one, two, or three arc lamps in series. By this system larger outputs may be got from one dynamo machine without excessively high pressures being used; since the current in the primary circuit may be greater, to any desired degree, than that required for the lamps. The lamps themselves are insulated from the high pressure circuit, and can therefore be introduced into

buildings without danger. Arc lamps of different candle-power requiring different currents, and incandescent lamps, could also be worked off the same circuit, by using transformers with different ratios between the primary and secondary windings.

(2) When the transformers are in series, and the lamps in the secondary circuit are in parallel, the transforming apparatus generally takes the form of accumulators, of which there must be two independent sets, one in the charging or primary circuit, and one in the discharging or secondary circuit; these two sets being arranged in such a manner that they can, either by hand or automatically, be changed over from the primary circuit to the secondary, and *vice versâ*, according to their state of charge. This system was worked out by the Chelsea Electricity Supply Co. in such a manner that all changes of connections and regulation of the accumulators were performed automatically at the distributing stations in which the batteries were grouped.*

The general arrangement of the primary and secondary circuits is shown in Fig. 16, in which the generating plant is marked D, and the double sets of accumulators in each distributing station are marked A, B. The three sets A A A are shown connected in series in the primary circuit for charging, whilst the sets B B B are shown discharging into the secondary circuits, in which the lamps are connected in parallel. Automatic apparatus is provided at each station, which can transpose the two sets, connecting B in the primary circuit, and A in the secondary circuit, or can connect the two sets A and B in parallel in the secondary circuit, at the same time disconnecting them from the primary mains, which are thus left free to be connected to motor-generators, which may be used to

* The Chelsea Co. have now adopted a different system of charging the batteries which is described in Chap. XVI.

supplement the supply at the times of greatest load. The secondary distribution from each station is effected in exactly the same way as though each station contained its own generating plant, and may be arranged on the simple parallel, or the three-wire system, with or without feeders, as the conditions of supply make one or the other the more convenient.

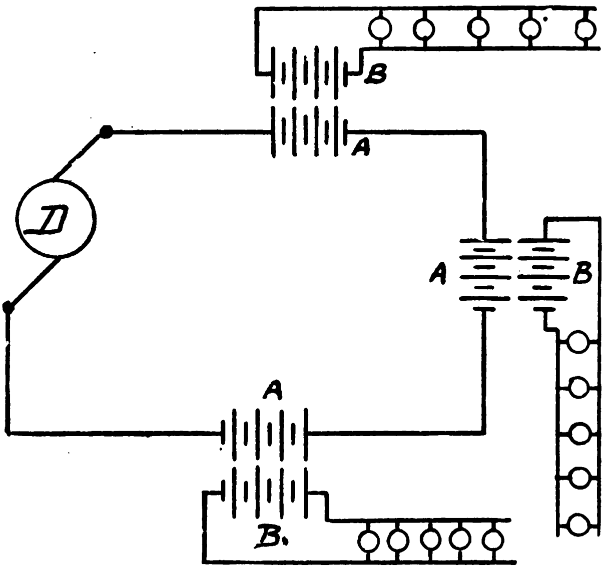

FIG. 16.

The advantages claimed for this system are: that the distribution to the lamps is effected at low pressure from substations, to which the current can be supplied at high pressure; that the use of accumulators is a safeguard against the failure of the supply through any accident to the generating plant, and permits of the total stoppage of all running machinery during the hours of light load; that the arrangement of the trans-

forming apparatus enables a greater maximum load to be supplied with the same generating plant, since this latter, exclusive of reserves, only has to charge one set of batteries at each station; whereas both sets may be coupled together, and their discharge supplemented by the current produced by the motor-generators at the time of greatest demand; and, finally, that the generating plant can always, when running, be worked at its most efficient load. On the other hand, the first cost of the accumulators is a very heavy item, and the annual charges for their upkeep, and for the electrical energy lost in them, must be set off against any increase of efficiency in the generating plant; so that it is probable that the advantages and disadvantages will nearly balance, and that whatever difference there is between the economy of this system and of others will depend on the life of the batteries, and this life cannot be definitely settled without a much more extended experience of their use.

(3) When the transformers are arranged in parallel in the primary circuit, the alternating current transformer is generally employed; the distribution being carried out, either by means of a high pressure network of conductors with a transformer in each building requiring current, or by high pressure feeders supplying transformers in substations, from which the current for the lamps is distributed by a low pressure system of conductors. In early days the first method was always employed, as it is especially suitable for supplying districts where the lights are somewhat sparsely distributed over a large area; but now, when the transformer system is used for the lighting of towns with even a very moderate demand for current per yard of main, the second method with a low pressure distribution is most in favour. With a high

pressure network, the difficulties of maintaining the insulation are increased by the necessarily large number of joints and connections in the distributing mains; and the energy wasted in the transformers is greater, when a separate one is fixed in each building, than it would be if a low pressure distribution from substations were employed; but against this must be set the

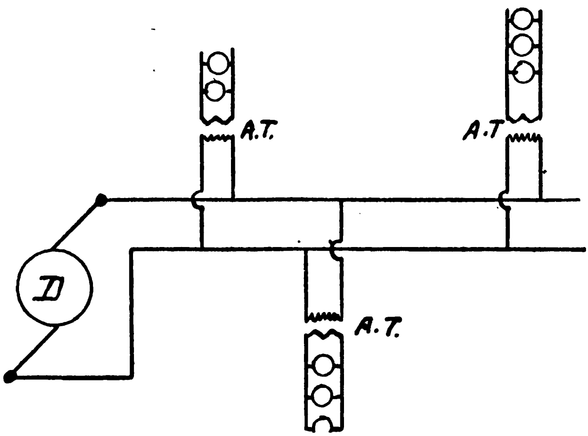

FIG. 17.

fact that the sectional area of the distributing conductors will be much smaller, and the fall of pressure more easily kept within reasonable limits.

The arrangement of the circuit with a transformer in each house is shown in Fig. 17, where D is the alternating current dynamo, and A T are the transformers. When calculating the variation of pressure at the house terminals, the loss in the transformer

must be taken into account; for instance, if the maximum variation of pressure at the house terminals is 5 per cent., 2½ per cent. of this must be allowed, as a general rule, for the transformer; leaving only 2½ per cent. for the conductors, or 25 volts on a 1000 volt circuit, and 50 volts on a 2000 volt circuit. If the economical current density be taken, say, at 1000

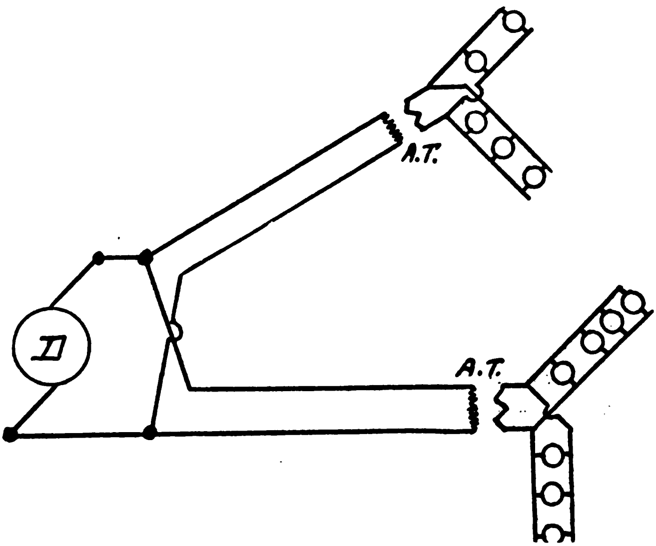

FIG. 18.

amperes per square inch, there will be a fall of pressure of 1 volt for each 38 yards of main; so that the maximum distance between the dynamo and the lamps is limited to 950 yards for a 1000 volt circuit, and 1900 yards for a 2000 volt circuit, unless feeders are employed, and the pressure kept constant at their far ends.

When transformer stations are used, and the current distributed from them at low pressure on the simple parallel, or the three-wire system; the pressure is kept constant at the secondary terminals of the transformer, and the high pressure conductors plus the transformers simply replace the feeder of the direct current system (see Fig. 18). This system is used with both continuous and alternating currents, but most frequently with the latter; indeed, there are only three or four stations in England using this system with continuous currents. At Oxford, which was the first to use it, the high pressure currents are delivered to motor-generators in substations at 1000 volts, and the current is distributed from the substations at 110 volts. All the motor-generators are controlled from a common switch station, and can be cut in or out of circuit according to the variations in the demand for current; thus making it unnecessary to run any motor-generator at less than half-load and considerably reducing the waste in the transforming apparatus.

When very great distances separate the generating station from the lamps, a double transformation may be employed; that is, the current may be transmitted from the dynamo to substations in the district to be lighted at extra high pressure, and from these it may be distributed either by means of a high pressure network with transformers in each house, or by high pressure feeders and low pressure distributing mains.

The economy of any of these transformer systems depends almost entirely on the efficiency of the transforming apparatus at varying loads; and this, though very high at full load, may be very small at the light loads which prevail during the greater part of the twenty-four hours. Although it is not possible to

draw any hard and fast line, which shall define the conditions under which the direct or the transforming system is the more efficient, some calculations will be given in the following chapter, which may serve to give a general idea of their relative economy.

CHAPTER V.

Relative Economy of Direct and Transformer Systems.—Energy Wasted in Conductors.—Effect of Load Factor.—Energy Wasted in Transformers.—Cost of Mains.—Insulated Cables in Conduits.—Armoured Cables.—Bare Copper in Culverts.—Cables for High Pressures.—Cost of Transformers.—Calculations of Total Annual Cost of Distribution.

Of the various systems of distribution mentioned in the preceding chapter, those which have been most extensively used are the two- and three- wire low pressure direct systems, and the two-wire high pressure alternating transformer system. The suitability of any one of these systems depends on the local conditions of the district, such as the distance of the farthest lamp from the generating station, the probable number of lamps per yard of main, and the annual and daily load factors: and it is therefore impossible to say that one or the other system is the best in all cases, as for each district the claims of the several systems must be considered on their merits.

In many cases it is advantageous to place the station outside the district to be lighted, so as to obtain a cheaper site, or cheaper coal or water, or to avoid all chance of causing annoyance by noise, vibration, or smoke. Another point to be considered is the relative economy of one large station serving an extended area, with a number of smaller ones, each serving a portion of the district; and many engineers are of opinion that economy and convenience will lead to the establishment of large supply stations on the outskirts of the towns, where land is cheap, where fuel can be easily delivered and refuse got rid of, where there is a good supply of water which will allow of the use of condensing engines with their increased economy, and

where the expenses of engineering supervision and general management may be less than would be the case if there were several stations placed in different parts of the district to be lighted. This removal of the station from a central position means either a great increase in the cost of mains or the use of high pressures, and this latter alternative necessitates the use of a transformer system, which lowers the efficiency of distribution, and has the disadvantage that at present the generating plant is more costly and less efficient than the plant required for the continuous current low pressure systems.

There is, however, a difference in the nature of the waste in the two systems, which to a large extent counterbalances the greater efficiency and cheapness of the low pressure plant; and that is, that in the latter case the greatest percentage loss takes place at the time of full load, whereas, with the transformer system, the efficiency increases as the load is increased. For an equal average waste, therefore, the ratio of maximum output at the station to maximum useful output is considerably higher in the direct system, when the mains are long; and the capacity of the plant must therefore be greater than that which is required for the same number of lamps on a transformer system. Taking this into account, it is probable that the cost of the unit of electricity delivered at the terminals of the dynamo is practically the same for both systems; and, in comparing the economy of direct and transformer distribution under different conditions, we shall make this assumption, and take the cost of a watt hour at £5×10^{-6} in all cases.

The waste energy, which has to be charged to the cost of distribution, is in the direct system entirely due to losses in the conductors; but in a transformer system,

the losses in the transformers themselves form a very large percentage of the total waste. To calculate the losses in the conductors, we must know the way in which the demand for current varies at different times, and the ratio of the average demand to the maximum demand throughout the year; and we shall assume 17 per cent. as a figure which represents fairly the annual load factor in an ordinary town district; and further, that the load curves are of such a shape as the one of which particulars are given on page 40. There we found that the current, which would, if steadily maintained throughout the year, give the same total waste of energy in the conductors as the varying currents actually transmitted through them, was about 26 per cent. of the maximum current, and this would give a loss equal to about $\frac{1}{15}$th of that which would be caused by the maximum current flowing continuously. With the transformer system there will be an appreciable increase in the amount of energy wasted in the conductors during the 6000 or 7000 hours of very light load, due to the exciting current required by the transformers; and to allow for this we propose to increase the total loss in the conductors to $\frac{1}{13}$th of that which would be caused by the maximum current.

The value assigned to the load factor has a very important bearing on the relative economy of the two systems of distribution; since with direct supply the whole loss is in the conductors, and any increase in the load factor, by making the equivalent current a greater percentage of the maximum, entails a greater waste in proportion to the square of this percentage; whereas, in the transformer system, only a part of the loss, and that a small one, is in the conductors; and therefore it is only this part of the total loss which is increased by the higher load factor. For example, suppose that

nine-tenths of the loss is in the iron tranformer core, and one-tenth in the conductors, when the load factor is 20 per cent.; if the load factor is then increased to 40 per cent., the ratio of the losses under the latter conditions to those under the former is expressed by $9+1\left(\frac{40}{20}\right)^2 : 10$ or $13 : 10$; whilst a similar increase in the average output with direct supply would make the losses four times as great.

The losses in the transformers depend, not only on the ratio of average to maximum load, but also in some cases on the ratio of the maximum number of lamps alight at any given time to the total number of lamps wired. This latter ratio must be taken into account, when a high pressure network with transformers for each house or pair of houses is employed; but it does not enter into the calculations, when the transformers are placed in substations from which the current is distributed by low pressure mains to the houses; and it is therefore necessary to consider these two cases separately. Suppose a house is wired for 50 lamps each of 60 watts, the transformer must be capable of supplying 3000 watts; although, except on very rare occasions, the maximum number of lamps alight at one time may be only 30, and the average load throughout the year may not exceed that due to 5 or 6 lamps. If we assume that the ordinary maximum load is 60 per cent. of the lamps wired, and that the average is 17 per cent. of this maximum; we find that the 3000 watt transformer will have an average output of 306 watts, or about 10 per cent. of its maximum. The losses in such a transformer may be taken as equal to 2½ per cent. of its maximum output for losses due to magnetization of the iron core, and say 2½ per cent. for losses in the coils at full load; that is, there is a continual

waste of 75 watts in the iron core; and, since the average output is only 10 per cent. of full load, the waste in the coils is about 2 watts. The average waste then is 77 watts, and the average output 306 watts; *i.e.*, the waste is at the rate of 250 watts for every 1000 watts supplied to the lamps, or ·0425 watt per watt of maximum load.

If we now consider the second case, where the maximum load is equal to the full output of the transformer; and we take larger transformers, such as would be used at the distributing stations, giving, say $1\frac{1}{2}$ per cent. loss in the core, and $2\frac{1}{2}$ per cent. in the coils; we shall find that the waste is at the rate of about 100 watts for every 1000 watts supplied to the lamps, or ·017 watt per watt of maximum load.

The next point to be considered is the sectional area of the conductors, the cost of insulating and laying them, and the percentage of this cost which is to be allowed for interest and depreciation. The area of the conductors has to be considered both as regards economy and variation of pressure, the latter determining in many cases the area of the distributing mains, whilst the former consideration decides the area of feeders, and also that of distributing mains, when these latter do not exceed a certain length depending on the permissible variation of pressure and the economical current density. Before we can decide on the most economical current density, we must know the actual cost of the mains in terms of the sectional area of the conductor, and we will therefore consider this matter first.

For low pressure mains, continuously insulated cable drawn into iron pipes or bitumen casing, armoured cables laid in the ground, or bare copper supported on insulators in a culvert, are most generally used

and, for each of these methods, the following estimated costs, which have been checked by comparison with the figures published from time to time, will, under ordinary conditions, be found fairly accurate.* In each case the cost of the completed main may be expressed as $L(ka + B)$, where L is the length in yards, a is the area of one conductor in square inches, and k and B are constants depending on the nature of the insulation and the system of laying. The value of B depends chiefly on the cost of opening up the ground and relaying the pavement, and on the cost of the pipe or conduit which is used for mechanical protection; while k is determined mainly by the quality and thickness of the insulating material.

The cost of an insulated cable does not, as a rule, vary in strict proportion to the area of the copper, the larger cables being relatively cheaper than the smaller ones; but from a comparison of the prices of different types of cable, it appears that for such sizes as are mostly required in low pressure systems, the cost per yard of cable may be taken as equal to £$(\cdot 775a + \cdot 050)$.

The cost of bitumen or stoneware casing or iron pipes, including delivery on the ground and material for jointing, varies from fifteen to eighteenpence per yard per 2-inch way; and the cost of surface-boxes and of excavating and laying the conduit under the pavement, allowing, say, three shillings and sixpence per yard for vestry charges, is about five shillings to five shillings and sixpence. A two-wire main may therefore be taken as costing per yard eight shillings, plus the cost of two yards of cable, or, say, £$(1\cdot 55a + \cdot 50)L$; and on the same lines a three-wire main, with the middle wire of half the area of either of the outside ones, may be taken as costing £$(1\cdot 95a + \cdot 65)L$, where a is the area of an outside conductor.

* These are average figures, and will vary with the prices of copper and insulating materials.

With armoured cables laid in the ground without the protection of a conduit, the cost of the latter is saved; but this is to some extent counterbalanced by the cost of the armouring. The cost of armouring does not vary exactly with the area, being proportionately more for small cables; and we may take without much error £$(1{\cdot}6a + {\cdot}45)$L for the cost of a two-wire main, and £$(2a + {\cdot}55)$L for that of a three-wire main.

The cost of the culvert for a bare copper system varies somewhat according to the different designs, but an average figure is from eighteen to twenty shillings per yard for a concrete culvert, with surface boxes, insulators, etc., including an allowance for vestry charges at the same rate as before. The copper strip, delivered on the ground, straightened and fixed in place, may be taken at ten shillings per yard per square inch section; and we may therefore put the cost of a two-wire main at, say £$(a + {\cdot}9)$L, and of a three-wire main at £$(1{\cdot}25a + {\cdot}95)$L. When this system is used, it is necessary in many places to put down insulated cables on account of the impossibility of finding space under the pavement for the bare wire culvert; and we propose therefore, to take the average cost of a low pressure main at a figure based on about equal lengths of bare wire and insulated cable, say £$(1{\cdot}3a + {\cdot}7)$L for the two-wire, and £$(1{\cdot}6a + {\cdot}8)$L for the three-wire main.

For the high pressure distribution insulated cables must always be used; and it is important that the insulation should be of the best and most durable quality, and that the cables should be laid, on a drawing in and out system, in pipes which afford good mechanical protection. Owing to the comparatively small area of the conductors, their cost, even when allowance is made for the more expensive insulation, is a much

smaller proportion of the total cost of the main than is the case in low pressure systems; and it is therefore economical to spend more in the first instance on the insulation, if a saving can be effected thereby in the cost of maintenance. The system which is most extensively employed in England for high pressure underground wires, is that in which rubber cables are drawn into cast-iron pipes; and we shall take as our standard a 3-inch cast-iron pipe containing two single cables of any area from ·02 to ·15 square inch, or one equivalent concentric cable. When a larger area is required, which however is not often the case with such pressures as 2000 volts, a second pipe can be laid in the same trench, or a larger pipe than 3-inch diameter may be used. The cost of opening up the ground, laying the pipe, including surface boxes, drawing in the cable, and vestry charges, is from seven shillings to seven and sixpence per yard, and the cost of the cable itself may be taken as £$(a + \cdot 035)$ per yard for single cable or as £$(2a + \cdot 095)$ per yard for a concentric cable. As the latter is most frequently used for alternating currents, we may take the cost of the main as £$(2a + \cdot 45)$L.

The rate to be allowed for interest and depreciation will vary a good deal under different circumstances; and it affects the economy of the system in this way, that a low rate is favourable to the low pressure system in which the first cost of the mains is heavy, whilst a high rate is favourable to the high pressure system; but as a fair allowance we shall take 10 per cent. for all systems on the whole cost of the distributing plant.

As regards the first cost of the distributing plant, we have still to fix on a price for the transformers themselves; and this we shall take at £6 per kilo-watt for the smaller transformers, each serving one or two

houses, which gives us £10 per kilo-watt of normal maximum load, owing to the fact that this latter is only 60 per cent. of the total number of lamps installed in each house; and at £4 per kilo-watt for the larger transformers placed in substations; these prices including fixing and accessories in both cases, and an allowance for the rent of a cellar, or the building of a transformer house or pit.

We can now proceed to make a comparison between the annual charges for distribution for the direct and transformer systems, taking as examples:—

1°. 200 volt two-wire direct system.

2°. 400 volt three-wire direct system.

3°. 2000 volt two-wire system with house transformers.

4°. 2000 volt two-wire feeders with substation transformers and 200 volt two-wire distribution.

We shall suppose that a circular ring main of length $2\pi L$ is fed by n feeders of length L, and shall calculate the annual charges for distribution for different values of L.

Let a = watts per yard of distributing main.

V = working pressure of main.

$\frac{2a\pi L}{Vn}$ = maximum current in each feeder.

$\frac{a\pi L}{Vn}$ = maximum current in any distributing main.

e = co-efficient for equivalent current = $\sqrt{\frac{1}{15}}$ for direct, or $\sqrt{\frac{1}{13}}$ for transformer system.

e_1 = co-efficient for uniform current in distributor = 0·6.

v_1 = maximum loss of pressure in distributors = ·05V for distributors without and ·025V for distributors with transformers.

p = proportion of cost for interest and depreciation = 0·1.

$(ka + B)$ = cost of one yard of main laid.

= £$(1·3a + 0·7)$ for two-wire low pressure.

= £$(1·6a + 0·8)$ for three-wire low pressure.

= £$(2a + 0·45)$ for two-wire high pressure.

T = cost of house transformers at £6 per kilowatt of maximum output of transformer

$$= £10 \times \frac{2a\pi L}{1000} = ·0628\, aL$$

T′ = cost of substation transformers at £4 per kilowatt of maximum output of transformer

$$= £4 \times \frac{2a\pi L}{1000} = ·0251 aL$$

t = hours of working = 8,760.

w = cost of one watt hour = £5×10^{-6}.

$A = 25·5 \times 10^{-6}$.

W = average loss in watts in house transformers $= ·0425 \times 2a\pi L = ·2669aL$.

W′ = average loss in watts in substation transformers $= ·017 \times 2a\pi L = ·1068aL$.

We first have to determine the best number of feeders, that is the value of n which will make the total annual charges on mains and transformers a minimum.

The annual charge on the n feeders

$$= \frac{4\pi Atwe^2 Da}{V} L^2 + \frac{2\pi pka}{VD} L^2 + pBnL$$

The annual charge on the distributing main

$$= \frac{4\pi twe^2 e_1^2 v_1 a}{V} \cdot L + \frac{2\pi^3 pkAa}{Vv_1 n^2} \cdot L^3 + 2\pi pBL$$

The annual charge on substation transformers

$$= (·1068twa + ·0251pa)\, L$$

The annual charge on house transformers

$$= (·2669twa + ·0628pa)\, L$$

The sum of these charges for distribution for any of the four systems will be a minimum when

$$pBL - \frac{4\pi^3 pkAa}{Vv_1 n^3} L^3 = 0.$$

$$\text{or } n = \sqrt[3]{\frac{4\pi^3 kAaL^2}{BVv_1}}$$

From this equation we can determine the best number of feeders to use for each system for various values of a and L; and then, having calculated the economical value of D by equating the two first terms of the expression for the annual charge on the feeders, we can, from the above expressions, calculate the total annual charges for distribution.

The results of such calculations are given in Table VIII. for the four systems for feeder lengths of 500, 1000, 2000, and 3000 yards, and for maximum outputs of 25, 50, and 100 watts per yard of distributing main. The annual charges due to interest and depreciation are given separately from those due to energy wasted in distributing apparatus, in columns headed p and w respectively, so that their relative importance under different conditions may be noted; and a column headed "Revenue" has been added, showing the revenue which would be obtained in each case if the Board of Trade unit were sold for sixpence.

An examination of this table shows that for all distances the 400 volt three-wire direct system is more economical than the 200 volt two-wire system, and that the gain is greater as the demand for current per yard of distributing main increases.

If we compare the 400 volt direct with the two transformer systems, we see that at 500 yards the direct always has the advantage; the second place being taken by the house transformer system when

TABLE VIII.

a	L.	200 volts direct, Two-wire.			400 volts direct, Three-wire.			2000 volts with house transformers.			2000 volts with sub-station transformers.			Revenue.
		p.	w.	Total.	p.	w.	Total.	p.	w.	Total.	p.	w.	Total.	
		£	£	£	£	£	£	£	£	£	£	£	£	£
25	500	388	36	424	371	24	395	255	155	410	358	71	429	2924
	1000	990	126	1116	890	77	967	564	316	880	844	148	992	5848
	2000	2717	470	3187	2282	275	2557	1275	662	1937	2104	325	2429	11696
	3000	5050	1033	6083	4086	595	4681	2092	1036	3128	3683	531	4214	17544
50	500	451	71	522	410	47	457	347	309	656	419	141	560	5848
	1000	1213	251	1464	1039	154	1193	755	633	1388	1007	296	1303	11696
	2000	3516	940	4456	2796	551	3347	1719	1324	3043	2558	650	3208	23392
	3000	6744	2066	8810	5150	1190	6340	2859	2072	4931	4534	1062	5596	35088
100	500	549	142	691	475	94	569	524	618	1142	522	282	804	11696
	1000	1577	503	2080	1262	308	1570	1138	1266	2404	1270	592	1862	23392
	2000	4848	1880	6728	3611	1102	4713	2572	2647	5219	3266	1301	4567	46784
	3000	9610	4132	13742	6904	2380	9284	4273	4145	8418	5841	2125	7966	70176

$a = 25$, and by the substation transformer system when a is greater. At 1000 yards the house transformer system leads when $a = 25$, but drops into the last place when a is greater, in which case the lead is again taken by the direct system. At 2000 and 3000 yards the order is house transformer, substation transformer, and then direct for $a = 25$ or 50; but with $a = 100$ the substation system takes the lead, the direct system being second at 2000 yards, and last at 3000 yards.

The load factor will affect the relative positions of these systems, as a lower one than we have assumed will be more favourable to the direct system, and a higher one to the transformer systems, because the fixed losses in the transformers are relatively more important the lower the load factor. We therefore see that the direct system is generally more advantageous when the demand for current per yard of main is high and the load factor low; and that the best conditions for the house transformer system are when the lamps are sparsely distributed over a large area, and when the load factor is high. The substation transformer system occupies an intermediate position, and is more especially suitable for districts where the demand per yard of distributor is high, but the generating station is at some considerable distance from the district where the current is used.

With regard to the average length of feeders that may be economically employed with the various systems, it would appear from the table that 1000 yards may be taken as the limit for the 200 volt system, and about 2000 yards for the 400 volt direct system; whilst the substation transformer system may be used with fair economy when the average length of the feeders is 1000 yards or over. The house transformer system is so much affected by the value of a

that it may be used for quite short distances when a is small; but when a is large, it is not so economical as the 400 volts at 2000 yards, nor as the substation system beyond this length of feeder.

CHAPTER VI.

Various Forms of Conductors.—Stranded Conductors.—Tubular Conductors.—Conductors of Strip or Sheet.—Jointing.—Straight Joints.—T Joints.—Joints in Concentric Cables.

THE shape of the section of a conductor, and whether it is solid or built up of a number of wires stranded together, may affect for equal sectional areas the rise of temperature due to the passage of an electric current, the fall of pressure along the conductor, the cost of insulating it, and the ease with which it can be handled. Conductors are generally of circular section, since this shape is the most convenient for covering with the insulating material; but rectangular strips are sometimes used, where the sectional area is large and the conductor is carried on insulating supports placed at intervals, instead of being insulated with a continuous covering. The circular conductor may be a solid wire, or may be built up of a number of wires stranded together; or it may take a tubular form, consisting either of a drawn tube of copper or of a number of wires laid up over a circular core. The solid wire is generally the easiest and cheapest to manufacture, but for wires of large area it is too rigid; and where flexibility is required a stranded conductor is used by preference. In England the ordinary practice is to use no solid wire larger than a number 14 L.S.G. (·080 inch. diameter); and even for smaller sizes, the stranded conductor is often preferred; but in America and elsewhere the solid wire is frequently used for larger sizes, more especially for overhead work.

The natural strands are those in which the largest number of wires are added in each layer, which will fill up the space and maintain a circular section, and the total number of wires in any such stranded conductors may always be expressed by $3n\ (n+1)+1$ where n is any whole number; the diameter of such a conductor, consisting of $3n\,(n+1)+1$ wires each of diameter d, is given by the expression $(2n+1)d$; for example, if wires are to be laid up round a central wire of diameter d, it is evident that the circumference of the circle passing through all their centres will be $\pi\ (2d)$ or $6{\cdot}28d$; and this will allow of six wires being laid up, which with the central one will give a seven-strand conductor having a diameter of $3d$. If to this another layer of wires is added, the circumference of the circle on which their centres must lie will be $\pi\,(4d)$ or $12{\cdot}56d$; which will allow of twelve wires being added, making a nineteen-strand conductor with a diameter of $5d$. Each successive layer will add $2d$ to the diameter, and will add a number of wires to the conductor, which increases by increments of six, giving a series as follows: 7, 19, 37, 61, 91 . . . . for diameters of 3, 5, 7, 9, 11 . . . . times that of the single wire.

The weight per unit length of the stranded conductor is always more, by an amount equal to from $1\frac{1}{4}$ to $2\frac{1}{2}$ per cent., than the weight of an equal length of the single wire multiplied by the number of wires in the conductor; owing to the fact that the wires are laid up in a screw thread path, so that each wire once in the lay completely encircles the strand to which it is being added. The resistance of a stranded conductor, if the several strands were insulated from one another, would also be more by the same percentage than the resistance of an equal length of single wire divided by the number of strands; but in practice the

strands are generally in good electrical contact with one another, and the current does not have to follow each single wire in its helical path, but passes in part across from one strand to another. If this electrical contact were perfect, the resistance would be less by this same percentage than that of an equal length of single wire divided by the number of strands; and we find, therefore, that in a conductor of n strands of wire, each having a resistance of R ohms per mile, the resistance per mile lies between $\frac{R}{n} \times (1+x)$ and $\frac{R}{n} \div (1+x)$, when $(1+x)$ represents the ratio of the weight of the stranded conductor to that of n single conductors. The actual value varies with the cleanness of the surface and the tightness of the stranding, and will be less with tightly stranded tinned copper than with loosely stranded plain copper. From actual experiment the author finds that with tinned copper wires the resistance is rather less than $\frac{R}{n}$; for instance, a 19/16 strand conductor built up of wires whose conductivity was found to average 99·86 per cent., showed an increase of weight by stranding of 1·67 per cent., and a conductivity by comparison of resistances and weights of 98·4, giving, therefore, a resistance equal to $\cdot 9982\ \frac{R}{n}$. The difference between the actual value and the calculated value of $\frac{R}{n}$ is so small that the resistance of the strand conductor may safely be taken as equal to the resistance of an equal length of the single wire divided by the number of strands, and consequently the effective area is equal to n times the area of the single wire.

If the resistance of a strand is compared with that of a solid conductor of the same diameter, it will be found that the former is from 28 to 33 per cent. greater than the latter, a fair average figure for the strands most generally used being about 30 per cent.; and if the diameters of a strand and a solid conductor having the same resistance are compared, it will be found that the former is from 13 to 15 per cent. more than the latter.

This increase of diameter over that of a solid wire of the same resistance will allow of a slightly larger current being carried for the same temperature rise; but unfortunately it also affects a much more important matter, viz., the cost of insulation, by adding about 30 per cent. on to the weight of insulating material that would be required to give the same resistance with a solid wire. With a view to overcoming this objection, a conductor built of segmentally shaped wires, which would fit close together and fill up the space left unoccupied by round wires, was proposed for one of the early submarine cables; but the diminished flexibility and the increased difficulties of laying up such wires prevented this form of conductor from being adopted. Such wires are, however, now used in building up the outer conductor of concentric cables, and when these are lead covered and armoured, the diminished flexibility is not appreciable.

When very great flexibility is required, the conductor may be composed of a number of strands each of which is itself a stranded conductor; or a number of very small wires, as many as 600 being sometimes used, may be twisted together at the same time, instead of being stranded up layer after layer in the usual manner.

The tubular form of conductor is sometimes used with alternating currents, because a large sectional area can then be employed with a smaller increase of virtual resistance than would occur with a solid wire; but its chief use is as the outer conductor of a concentric cable, that is a cable which contains both the out and return conductors, the outer one taking the form of a tube which entirely encloses the inner conductor and its insulating covering. The advantages of placing the two conductors concentrically are, that with alternating or unsteady currents, the inductive action of one conductor on neighbouring wires is neutralized by that of the other conductor; and that with any current the system of conductors can be so arranged that the inner conductor cannot be touched, and cannot make any contact with earth, without first making a contact with the outer conductor.

The first point is of considerable importance where the conductors pass very close to the wires of telephone circuits; but, under ordinary circumstances, no serious interference with the working of the telephones is caused by two separate well insulated conductors lying close side by side in the same pipe; and it is therefore very doubtful whether, for this reason alone, the advantage gained by the use of the concentric cable is sufficient to counterbalance the greater difficulties of jointing, and the increased cost of insulation, when the outer conductor is required to have the same resistance from the earth as the conductors of either of the separate cables. Where very high pressures are used, and accidents might arise from the handling of the cable, the fact that the outer conductor, which alone is accessible, is very nearly at the same potential as the earth is a great safeguard; but this state of affairs only continues so long as the insulation of all parts of

the circuit is perfect, unless the outer conductor itself is in some way connected to earth.

The fact that any leakage from the inner conductor must be to the outer one, and that it is therefore of the nature of a short circuit, is claimed as a safeguard against fire in ships or buildings wired with these cables, since the circuits can be protected by fusible cutouts, and any excessive leakage from the inner conductor will blow the fuse and stop the supply of current.

When the outer conductor of a concentric cable consists of n wires laid up round the insulated inner core, each wire having a resistance of R ohms and a weight of W lbs. per mile, the weight of the conductor per mile will be from 1·03 to 1·04 times nW, and the resistance will be equal to $\frac{R}{n}$ multiplied by the same constant. This case differs from that of the strand conductor in that the electrical contact between neighbouring wires is very imperfect, and it is unsafe to count on a resistance lower than that which would be given if the wires were insulated from another. We see, therefore, that the resistance of the outer conductor of a concentric cable is from 3 to 4 per cent. greater than that of a strand conductor built up of the same number of wires of the same diameter, from 4 to 6 per cent. greater than that of a strand conductor of the same weight, and from 6 to 8 per cent. greater than that of a solid conductor of the same weight.

As regards the rectangular sectioned conductor, Professor George Forbes, in a paper on "The Prevention of Heating of Conductors," read before the Society of Telegraph Engineers in 1884, showed that strips or sheets of comparatively thin metal could, for the same

rise of temperature, carry much heavier currents than round wires, and advantage is sometimes taken of this fact when the conductors are bare; but when they have to be covered with a continuous coating of insulating material, the increase in the cost of the insulation will more than counterbalance any gain due to the smaller weight of copper required to carry the current.

The jointing together of two conductors is an operation which has frequently to be performed, the method adopted depending on the size and shape of the conductor, and on whether the joint is to be insulated or not; but in all cases the first desideratum is, that the surfaces in contact shall be of considerable area, and that the contact itself shall be as perfect as possible, so that there may be no undue heating owing to any increase of resistance at the joint. With very large conductors, or conductors that have not to be covered with insulating material, the joint may be made by securely clamping the two ends together, care being taken that the surfaces are well cleaned and tinned; and this plan is also adopted in many cases where, for testing or other purposes, it is desirable to be able to break the joint at any time. The general method is, however, to connect the two conductors together by the use of solder, supplemented when they are to be subjected to tensile strains by binding them with wire, splicing them, or enclosing the ends in special couplings.

An excellent joint for an overhead solid wire is made as shown in Fig. 19, in which the end of each wire is bent up, and the two wires fixed side by side in a vice and tightly bound with binding wire, and the whole soldered together. The binding wire should by preference always be of the same material as the two

wires which are being jointed, and if the wires are of hard drawn copper, care should be taken to heat them only just enough to make the solder run freely; as the use of a very hot iron, or a long-continued application of the heat will weaken the wire very considerably.

FIG. 19.

For stranded conductors couplings are sometimes used, such as the one shown in Fig. 20, which consists of a tubular piece of metal enlarged in the middle so as to form a double cone, and provided with an opening at the centre. The stranded conductor is pushed through the hole at the end and brought out at the central hole. It is then doubled back on itself, and is pushed back through the central opening, and pulled so that it jams

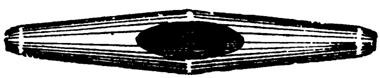

FIG. 20.

itself tight in the cone-shaped coupling. When both conductors are fixed in this way, solder is run in through the central hole so as to keep them in place and improve the contact.

When the conductor has to be insulated, it is im-

portant that the joint shall be as nearly as possible of the same diameter as the conductor itself, and that it shall present a perfectly smooth surface, a result which can best be obtained by the following methods:—

For a solid wire or a 7-strand conductor, the scarf joint shown in Fig. 21 is the best to use. Each conductor, if stranded, is soldered up into a solid wire, and the ends are filed to a long bevel so as to obtain a large surface of contact. The two conductors are then clamped together in a vice, bound tightly together with tinned copper binding wire of small diameter,

FIG. 21.

and soldered; after which the surface is smoothed by filing, so that there are no projections which may pierce the insulation. Resin should always be used as a flux, either raw, or dissolved in spirits of wine, when it takes the form of a thin paste; and the wires should be carefully cleaned before being bound together, so as to ensure that the solder will take freely on them.

For conductors of 19 strands or more, either a married or a telescope joint may be made. To make a married joint, a few turns of binding wire are wrapped round the conductor to keep the strands in place, and the outside wires are then turned back so as to expose the central strand. This is soldered up solid and scarfed, and the central strands of the two conductors are

jointed in the manner already described. The outside wires are then cut off to suitable lengths, alternate ones on each conductor being short and long (Fig. 22), and the two sets of wires are laid on over the central

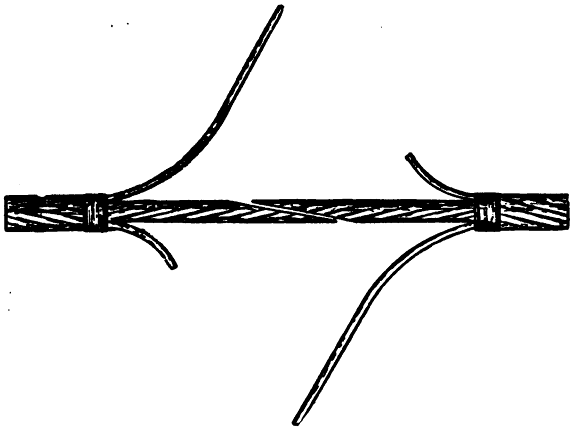

FIG. 22.

strands, so that a long wire of one set butts up against a short wire of the other set. By this means half the joints in the separate wires are at each end of the joint in the conductor. The joint is then whipped with

FIG. 23.

binding wire at each end, and soldered (Fig. 23), and the surface smoothed up with a file. In very large conductors, where flexibility is wanted, the marrying may be repeated; as for example, with a 61-strand conductor, a scarfed joint may be made of the 19 central strands; the surrounding layer of 18 wires

may then be married together, the joints being arranged to come a couple of inches or so beyond the scarf on each side, and the surrounding layer of 24 wires may be married, so that the joints come a few inches outside these again. In each case the joint is only soldered just at the place where the separate wires are butted together, and by this means a joint can be made which can be bent about without much difficulty.

To make a telescope joint, the outside wires of one conductor and the inside wires of the other are cut off short (Fig. 24), a binding being put on first to keep the

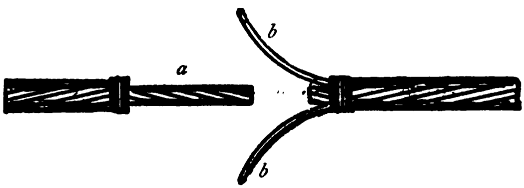

FIG. 24.

strands in place. The central strands *a* are soldered up solid, and the outer strands *b b* are laid up again in place, so that they form a hollow cylinder, into which the projecting end *a* is pushed. A few turns of binding wire are put on over the wires *b b* to hold them firmly in place, and the joint is then soldered.

Besides the straight joint between two conductors, there is also the T joint, where a smaller wire is branched off from a main cable. If the branch wire is a solid wire it may be wrapped spirally round the larger conductor, and soldered to it; but care must be taken that the branch wire is not soldered right up to the point where it leaves the larger conductor, as it is then apt to get broken off, if bent. One turn of the

spiral may be left unsoldered, or the wire may be laid in lengthwise of the strand for half an inch or so (Fig. 25). When the branch is a 7-strand conductor, the wires should be unstranded, and three of them

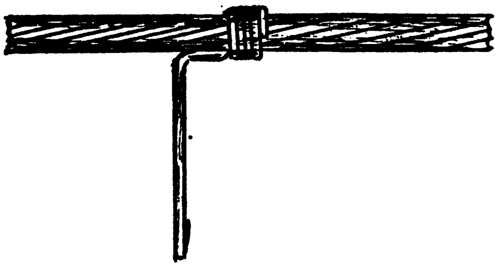

FIG. 25.

laid up spirally around the main conductor in one direction, whilst the other four are laid up round it in the reverse direction (Fig. 26); the ends only of these spirals being soldered, so as to permit of the branch

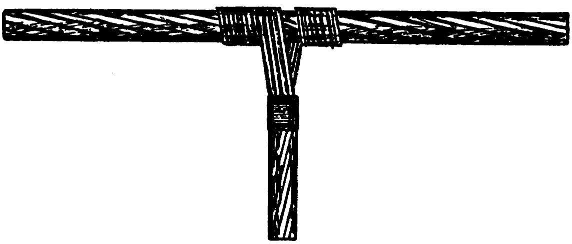

FIG. 26.

being bent to one side or the other, without danger of breaking off any of the wires.

When both conductors are large, it is better to make a Y joint rather than a right-angled T joint. This is done by soldering both conductors up solid, scarfing the branch conductor, and filing a recess in the main conductor, into which the scarfed end will fit. The

two conductors are then bound together and soldered, as shown in Fig. 27.

The joints in the inner conductors of concentric cables are made in much the same way as joints in ordinary single-core cables, but the outer conductors require somewhat different methods. For a straight joint the inner conductor is scarfed or married accord-

FIG. 27.

ing to its size, and is then insulated; the wires forming the outside conductors having been turned back out of the way. A sleeve of tinned copper is then placed over the inner insulation, and the outer wires are laid up over it, married, bound with binding wire, and soldered in the way already described.

For a T joint the wires of the outer conductor are

FIG. 28.

cut through and turned back, the inner conductor is branched off and insulated, and a sleeve (Fig. 28) is folded over the insulation, so that the branch wire passes out clear through the central hole. The outer conductors of the main cable are then laid up, bound and soldered to the copper sleeve, and the outer wires of the branch are separated into two sets, and laid in

spirally over the sleeve, as shown in Fig. 29. The making of such a joint requires very great care to avoid injuring the inner insulation, whilst making the

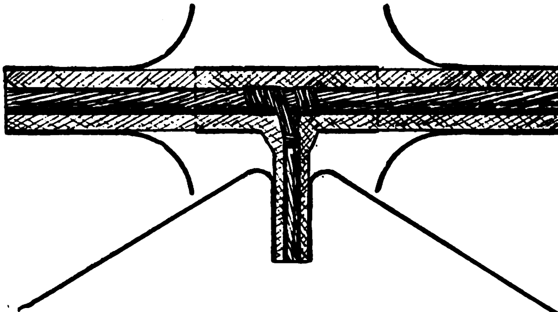

FIG. 29.

joint in the outer conductor, and takes longer and is more difficult to make than two joints in separate conductors. In the Andrews system of concentric wiring,

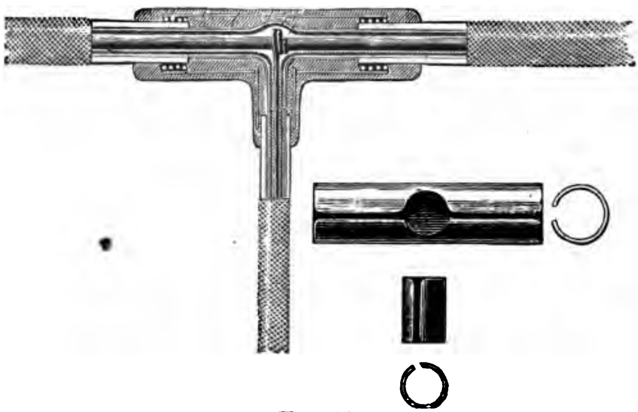

FIG. 30.

the inner joint is made as already described, it is then insulated, and over it are placed two copper sheaths which together make a T piece (Fig. 30), and enclose

the ends of the outer conductor, which in this system is connected to earth. An iron mould is then fixed round the joint by screws, and a molten metal with a low fusing point is poured into it; the mould when the joint is cold is removed, leaving the sleeves and a short length of each outer conductor beyond them enclosed within a mass of metal.

CHAPTER VII.

Insulating Materials.—Air Insulation.—Objections to its Use.—Resistance of Bare Wire Circuits; of Solid Insulators; of Insulated Cables.—Effect of Temperature on Specific Resistance of Insulators.—Effect of Pressure on Insulation Resistance.—Minimum Resistance of Circuit for fixed Percentage of Waste by Leakage.—Shocks due to Faulty Insulation; to Electrostatic Charge; to Condenser Current.—Disruptive Discharge.—Tests on Breaking Down Pressures.

When a generating and receiving apparatus are connected in a circuit in which a current is passing, it is necessary to insulate the conductors which form the connecting link between them, so as to prevent the current from finding any other path by means of which it can return to the generator, without first passing through the receiving apparatus. This insulation may be effected by surrounding the conductor along its whole length by a material or materials offering a very high resistance to the passage of the current, such as dry air, glass, ebonite, porcelain, wood, slate, mica, silk, cotton, or other fibrous materials, paper, india-rubber, gutta percha, and a variety of oils, waxes, and resinous or bituminous compounds. Some of these, such as wood, silk, cotton, paper, etc., lose their insulating properties to a very great extent when damp; and as there is always a certain amount of moisture in the atmosphere, it is necessary to protect such substances, when used as insulators, from exposure to the air by means of a waterproof covering. Besides preventing leakage sufficient to cause an appreciable waste of energy, or to give an unpleasant shock to any one touching a part

of the conducting circuit, the dielectric should be of such a kind as will allow of the insulated conductors being handled with impunity, and of sufficient thickness to prevent a disruptive discharge from one conductor to another, or from either to the earth.

There are two distinct methods by means of which it is sought to obtain these results: in one the conductor is supported at intervals on blocks of insulating material, and elsewhere is surrounded by air; and in the other the conductor is completely enclosed in a continuous covering of insulating material. The former may at first sight appear the more advantageous, since air is a cheap form of insulator; but unfortunately the air is not as a rule dry, and the film of moisture which condenses on the surface of the insulating support (especially when the latter is itself not perfectly clean), forms a fair conductor of electricity; and thus causes the insulation of a bare wire line to be very low in damp weather when the number of supports is large. There is also the danger of a short circuit between two conductors, which may be caused by their swaying so as to touch one another, or by some conducting material falling on them so as to bridge from one to the other. The conductor being bare, it must be placed in such a position that it cannot be touched accidentally by linesmen or others; unless the pressure is so low that no harm could result from a shock from it. When high pressures are used, there is the further disadvantage that the sparking distance through air for equal pressures is considerably greater than that through other insulating materials, and that this sparking distance is greater still when there are dirty surfaces over which the spark may travel. In the majority of cases one or more of these reasons make it impossible to take advantage of the cheapness of air insulation;

and continuously insulated conductors have therefore to be used.

The insulation resistance of any air-insulated bare wire circuit depends entirely on the number of supports, and on the resistance of each one of them; and as the greater part of the leakage which takes place at each support is over the surface of the insulator, this resistance is by no means constant, but varies with the state of the surface, whether clean and dry, or dirty and wet. When the surface is clean and dry the resistance may be very high; and even when wet, if the surface is clean, as happens sometimes after very heavy rain, a good test may be obtained; but when the insulators are dirty and the air full of moisture, the result is different, the insulation resistance under these conditions falling off very considerably. The shape of the insulating support is arranged so as to give as great a length of surface as possible, over which the leakage current must pass before it can get from one conductor to another, or from either to earth; and the supports are fixed in such positions as will allow of the smallest amount of dirt collecting on them. Besides leakage over the surface, there is also a certain amount which passes through the body of the insulating material, the resistance to which is proportional to the mean length of the current path, and inversely proportional to the area over which the current can spread itself, following therefore the same law as the resistance of all conductors.

Owing to the fact that the specific resistance of most insulating materials varies much more than that of good conductors, the calculation of the resistance of the former from their dimensions gives less certain results; indeed, many of the insulating materials named above can hardly be said to have a definite

specific resistance, owing to the difficulty of reproducing them under exactly the same conditions at different times; and this is particularly the case with those materials whose power of absorbing moisture is appreciable. The insulation resistance of a cable covered with such a material cannot be predetermined with any great degree of accuracy; but with materials whose specific resistance can be relied on, the resistance of the cable can be calculated, if we assign correct values to the length or thickness, and to the area of the covering. These dimensions are obtained in the

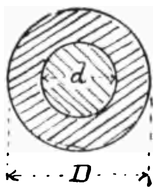

FIG. 31.

following way for circular conductors:—Referring to Figure 31, which shows a transverse section of the insulated conductor, we see that for unit length, as we get farther from the centre, the area of a layer of insulating material increases, and that therefore successive layers of the same thickness will not add equally to the insulation resistance. Suppose then that the insulating material is divided up into a large number of concentric layers of varying thicknesses such that each layer offers the same resistance ρ, and that there are n such layers, so that $n\rho$ is the resistance of the cable; then, if d_m and d_{m+1} are the internal and external diameters of any layer, the resistance

$$\rho = \frac{(d_{m+1} - d_m)}{2\pi d_m l} \times s,$$

where s is the specific resistance of the insulating material and l the length of the cable. This equation may be written

$$d_{m+1} = d_m\left(1 + \frac{2\pi\rho l}{s}\right)$$

which shows that the outer diameter of any layer, whose resistance is ρ, is equal to the inner diameter of the same layer multiplied by a constant $\left(1 + \frac{2\pi\rho l}{s}\right)$. Applying this to find the outer diameter d_{m+2} of the next layer, the inner diameter of which is d_{m+1}, we get $d_{m+2} = d_{m+1}\left(1 + \frac{2\pi\rho l}{s}\right) = d_m\left(1 + \frac{2\pi\rho l}{s}\right)^2$. By similar reasoning we see that the outer diameter of the nth layer is expressed by $d_{m+n} = d_m\left(1 + \frac{2\pi\rho l}{s}\right)^n$. Putting D the outer diameter of the insulated conductor for d_{m+n}, and d the diameter of the conductor for d_m, we get $D = d\left(1 + \frac{2\pi\rho l}{s}\right)^n = d\left(1 + \frac{2\pi R l}{sn}\right)^n$, where $R = n\rho$ is the insulation resistance of the cable. By substituting $\frac{1}{x}$ for $\frac{2\pi R l}{sn}$ we can write the equation thus

$$D = d\left(1 + \frac{1}{x}\right)^{\frac{2\pi R l x}{s}} = d\left[\left(1 + \frac{1}{x}\right)^x\right]^{\frac{2\pi R l}{s}}$$

The larger the number of layers the nearer is the approach to absolute accuracy, therefore we may suppose $n = \infty$ in which case $x = \infty$; and when $x = \infty$ then $\left(1 + \frac{1}{x}\right)^x = e$, the base of the Napierian logarithms,

$\therefore D = d \times e^{\frac{2\pi R l}{s}}$ or $\frac{D}{d} = e^{\frac{2\pi R l}{s}}$, which gives

$$\log_e \frac{D}{d} = \frac{2\pi R l}{s}$$

or $R = \frac{s}{2\pi l} \log_{\epsilon} \frac{D}{d}$.

$$\text{But } \log_{\epsilon} \frac{D}{d} = 2{\cdot}3026 \ \log \frac{D}{d},$$

$\therefore R = \frac{s . \log \frac{D}{d}}{2{\cdot}728 l}$, and this equation shows that the mean value of $\frac{\text{length}}{\text{area}}$ is expressed by $\frac{\log \frac{D}{d}}{2{\cdot}728 l}$.

From this equation we see that the insulation resistances per statute mile of two cables covered with the same material will be proportional to the logarithms of the ratios of the external and internal diameters of their insulating coverings; and therefore, that with the same insulating material, this ratio will be a constant for all cables having the same resistance, no matter what is the diameter of the conductor.

The specific resistance of any insulating material is affected by temperature, but in the opposite sense to that of conducting materials; that is to say, that an increase of temperature lowers the specific resistance, and this at a much more rapid rate than it increases the resistance of conductors. For example, whereas a rise of 20° Fahr. only increases the resistance of a copper wire by rather more than 4 per cent., the same rise will reduce the resistance of some gutta perchas to about 20 or 25 per cent. of its initial value, and a rise of 40° Fahr. which would add less than 9 per cent. to the resistance of copper wire, may reduce the resistance of gutta percha to about 5 per cent. of its initial value. All insulating materials are affected in the same way, though with many of them it is to a smaller extent; but no figures can be given, either of the specific resistance or of the temperature coefficients, which can be

depended on as reliable for general use, as the variations are so considerable for slight differences in the composition of the insulating material and in the treatment it receives during manufacture. It must not be thought by this that the manufacturer is never able to predetermine the resistance of a cable; because this can be done with many materials, so long as they are mixed and treated in exactly the same way, in which case there is a definite specific resistance; but, if any change is made in the material or in the treatment of it, it is necessary to redetermine the values by experiment, as they may be altered very considerably by changes in the process of manufacture.

It has been alleged also that the resistance of a cable varies according to the pressure at which it is tested, and experiments have been made from time to time to test the accuracy of the statement. The question, as to whether the resistance decreases with increase of pressure, is of considerable importance, now that extremely high pressures are being used; because, if the effect of increased pressure, when maintained for a few minutes only, is to decrease the resistance, we may expect that the continued application of a high pressure will have a very marked deteriorating effect on the material. It is only on account of this aspect of the question that the matter has any serious practical importance, as a falling off of several per cent. in the insulation resistance of the cable at a high, as compared with that at a low pressure, is of no moment in itself; since, as a general rule, the effect of coupling up transformers, switches, cut outs, or other apparatus in circuit with the cable, is to lower the resistance of the circuit by perhaps 80 or 90 per cent.

In making comparative tests with different battery powers there are many obstacles in the way of attain-

ing really accurate results, such as the difficulty of maintaining an absolutely constant temperature, of wiping out residual charges, of maintaining the ends of the cable under permanent conditions as regards surface leakage, and the possibility of introducing errors through comparing very large and very small deflections, or through using shunts the temperature co-efficients of which may differ from that of the galvanometer coils.

Even when repeating tests with the same battery power on different days, it is by no means uncommon to get results which differ from one another by 5 per cent. or thereabouts, unless the most extraordinary precautions are taken; and one must therefore be careful not to jump to conclusions from the results of a few tests, unless the difference of insulation resistance with different pressures is very marked. Probably the first carefully conducted series of tests in connection with this matter is that which was made by Herr Heim, who compared the insulation resistances of a gutta percha core, and of two lead-covered cables at pressures varying between 21 and 460 volts. From the published description of these experiments, it appears that great precautions were taken to ensure accuracy, and corrections were made for the small temperature variations which could not be avoided, for leakage of testing instruments and leads, and for residual charge; but even in these tests there is a considerable want of uniformity in the results, the variations, when resistances were measured at different times with the same battery power, being of about the same magnitude as those which were obtained when they were measured with widely varying battery powers. For instance, with the gutta percha core, the fall of insulation resistance resulting from an increase

of pressure from 52 to 460 volts, taken as the mean of eight tests, is given as 6·6 per cent., the smallest recorded fall of insulation is 4·6 per cent., and the largest is 10·6 per cent., showing a variation between two of the tests of nearly the same magnitude as the average percentage fall due to the increased pressure.

In a similar manner one of the lead-covered cables, on which only four tests are recorded, shows a mean fall of 5·3 per cent., a maximum of 8·1 and a minimum of 2·2; whilst the other, also as the result of four tests, shows a mean of 2·9, a maximum of 3·8, and a minimum of 2·3 per cent. Comparing tests made at the same pressure but on different days, one finds that there were variations of as much as 7 per cent., even after making a proportionate correction for the small differences in temperature which are recorded; and it is difficult therefore to follow the experimenter when he concludes that "the experiments, therefore, prove that a fall in the insulation resistance does undoubtedly take place as the pressure increases in the cases of the cables that I tested." All the recorded results show a fall of resistance with increased pressure; but the fact that the figures obtained vary amongst themselves in the manner mentioned above, shows that a much larger number of concordant results is required before the proposition can be considered to be conclusively proved. As further tending to show that the question is still an open one, we may mention, that in a leading article in one of the technical journals, some tests on rubber cables were quoted in which pressures varying between 15 and 600 volts made very little difference in the resistance, and this difference was not always in the same direction.

More recently, Mr. Preece, in a paper presented to

the Institution of Electrical Engineers, quoted tests showing that for an increase of testing pressure from 15 to 600 volts, there was no decrease of the insulation resistance of a gutta percha core; but, in the discussion which followed, Mr. Siemens published the results of a series of tests in which the difference of insulation resistance was much greater than can be accounted for by the small errors of measurement to which we have already referred. The battery used in these tests varied from 100 to 1200 Leclanché cells, giving, say, from 150 to 1800 volts; and the observed results show that with 100 cells the insulation resistance was greater than that with 1200 cells by the following percentages:—For gutta percha core, about 15 per cent.; for high insulating india-rubber core, about 29 per cent.; for lead-covered cable, with what was called C impregnation, about 56 per cent.; and for lead-covered cable with A impregnation, about 18 per cent. These results, showing such a marked fall of insulation resistance with increased testing pressure, are very difficult to explain; as Mr. Siemens stated on the same occasion that some cable, which was working at 20,000 volts for a few hours every day at the Frankfort Exhibition, had practically the same insulation resistance when returned to his works as before it was sent to Frankfort; thus showing that the continued application of a high pressure did not permanently lower the insulation resistance.

Looking merely at the probability of a decrease of insulation resistance resulting from an increase of pressure, there are one or two points which may be considered. The important question is, what is the effect on the dielectric of the continued passage of a small leakage current. We know that the flow of a current against an opposed resistance must be accom-

panied by an expenditure of energy which may produce either heat or chemical action, or both; and if we suppose that heat is generated, then owing to the fact that all insulating materials are bad conductors of heat, there must be a rise of temperature in the interior of the dielectric as compared with the water in which it is immersed. If the current is kept on for any length of time this might account for a fall in the value of the insulation resistance, but it is difficult to imagine such a result manifesting itself immediately the circuit is closed. Chemical action may certainly in many cases lower the resistance; but here again we are met by a difficulty, since any such fall due to chemical action is not likely to be a temporary one, but on the other hand may be expected to cause a permanent deterioration; whereas in all the experiments, the results of which have been published, a repetition of the test with a low battery power is stated to have given nearly the same resistance as was obtained before the high pressure was applied, showing that according to these tests the falling off of resistance is only temporary.

That a permanent deterioration may be caused by using a pressure nearly as great as that which would break down the insulation and cause a disruptive discharge, is certain; since experiments show that if a pressure of say 10,000 volts will break through a given thickness of insulating material immediately it is applied, then a lower pressure, say 8,000 volts, will break through the same thickness of similar material, if the application is continued for some hours. There is, so far as we are aware, no direct proof that pressures much below the breaking-down pressures will have a similar effect, but it is quite possible that this will be the case, if only sufficient time is allowed. If we accept this view, a strong argument for high insulation resist-

ance is furnished, since the higher the resistance, the smaller will be the leakage current, and therefore the less will be the chance of its producing any deterioration of the insulating material. Whatever conclusion may be arrived at, it is certain from the results of actual daily use of well insulated cables, that the deterioration, if it takes place at all, takes place very slowly, when the pressure is kept well below that which would break down the insulation entirely; and as a further example of this, we may mention the case of some vulcanized rubber cables which had been in use underground for several years, at 2,400 volts, by the London Electric Supply Corporation, and were withdrawn from the pipes in order that they might be made into concentric cables; as these cables, which originally had an insulation resistance of about 5,000 megohms per mile at 60° Fahr., gave practically the same when tested after being taken up.

The total amount of leakage that can be allowed on any circuit depends on the permissible waste of energy, and this may be taken as a percentage of the output; and also on the maximum current which may be passed with safety through the body of any one taking hold of one conductor whilst at the same time making good earth.

The waste of energy will always be the same percentage of the total output if the insulation resistance of the whole circuit varies as the quotient of the pressure of supply by the average current; that is to say, with the same pressure the insulation resistance may vary inversely with the current; with the same current it may vary directly as the pressure; and with the same output at different pressures it may vary as the square of the pressure. For example, suppose it has been decided that the leakage waste may equal

$\frac{1}{5000}$th of the output, then the insulation resistance R_i of the circuit must be at least equal to $5{,}000 \times \frac{E}{C}$; or say with 100 volts and 100 amperes $R_i = 5{,}000$ ohms: with 100 volts and 500 amperes $R_i = 1{,}000$ ohms; with 1,000 volts and 100 amperes $R_i = 50{,}000$ ohms; and with 1,000 volts and 50 amperes (that is the same output as in the second case) $R_i = 100{,}000$ ohms.

As regards safety from shocks caused by touching one conductor, the absolute value of the leakage current which may pass through the body, must not exceed a fixed amount, and therefore the insulation resistance of the circuit should vary directly as the pressure of supply. The resistance of the part of the body in circuit and of the contacts will affect the amount of current passing, and as the value of this resistance may vary considerably according to circumstances, it is difficult to lay down a definite rule. According to experiments made by Messrs. Lawrence and Harries, the average resistance from hand to hand, when grasping a pair of metal electrodes, is about 6,000 ohms for continuous currents, and about 4,000 ohms for alternating currents. The results of experiments made by Mr. Swinburne also give a resistance to continuous currents of about 6,000 ohms, when the hands are dry; but this figure is reduced to about 2,000 ohms when the hands are moistened with dilute acid. The resistance to alternating currents, however, comes out much lower in these experiments, averaging about 1,000 ohms only, when the resistance of one subject which was phenomenally high is left out of account.

The two sets of experiments also show a considerable difference in the amount of current which may be passed through the body without injury; Messrs. Lawrence and Harries giving an average of ·018 ampere as the

value of the continuous current which becomes really painful, and rather over ·004 ampere as that of the alternating current. They also found that muscular fixation, that is the inability to leave go of the electrodes, was caused with an alternating current of rather less than ·008 ampere. Mr. Swinburne found that all the subjects of his experiments could stand more than ·018 ampere continuous current, and one actually stood ·044 ampere, and could have taken more if it had been available. With alternating currents the amperes varied from ·014 to ·030, according to the resistance of the subject, the pressure between the two electrodes being 18 volts, and under these conditions there was no difficulty in letting go.

Since, in cases of this kind, it is always best to have a large margin of safety, we may take it that there will be absolutely no danger if the current, which can pass through any one's body, does not exceed ·01 ampere continuous, or ·002 ampere alternating; and assuming the lowest value of the average resistance, viz., 1,000 ohms, we then find that the insulation resistance of the circuit should be at least $\frac{V}{\cdot 01} - 1{,}000$ for continuous currents, and $\frac{V}{\cdot 002} - 1{,}000$ for alternating currents, when V is the pressure of supply. These expressions may be written 100 V – 1,000 and 500 V – 1,000, and give the following values for the required insulation resistance of the circuit:—For continuous currents, 9,000 ohms for 100 volts pressure, 99,000 ohms for 1,000 volts, and 199,000 ohms for 2,000 volts; and for alternating currents, 49,000 ohms for 100 volts, 499,000 ohms for 1,000 volts, and 999,000 ohms for 2,000 volts; or, neglecting the resistance of the body, 100 ohms and 500 ohms respectively for each volt of

pressure. As a matter of fact, the resistance at the point of contact between any part of the body and the conductor is generally, when the contact is accidental, very considerable; and therefore the resistance opposed to the passage of the current is much higher than that given by experiments, in which the subject grasps two metal electrodes, and the current passing through the body is less; so that we find that, with low pressures, the conductors can be handled with impunity even when the insulation resistance is lower than that named above. The Board of Trade regulations for securing the safety of the public require that the insulation of every circuit, including all apparatus connected thereto, shall be so maintained that the leakage current shall not exceed $\frac{1}{1000}$th of the maximum supply current.

There is, however, always the chance of making a really good contact, and full precautions should therefore be taken to guard against accidents arising from this cause. One of these precautions, which is a very self-evident one, is to reduce the amount of exposed conductor to a minimum; and to arrange the conductors, where they must of necessity be left bare, in such a manner that access can only be had to them by persons whose business it is to keep the circuits in good order, and who, one may suppose, will take proper precautions when handling them. Accidents have sometimes happened through a linesman, working on a conductor which has been put out of circuit, coming into contact with a neighbouring wire in which a current is flowing; and therefore, unless the wires of a circuit are so far removed from all other wires as to render such an occurrence impossible, it is advisable in all cases to cover them with a continuous

insulating coating, which, to be of any service, must be waterproof, so that its insulation remains unimpaired under all conditions of working.

Thus far we have only considered the case of a shock caused by faulty insulation; but, under certain conditions, it is quite possible to get a shock if contact is made simultaneously with the earth and one conductor, even although the insulation of the circuit is perfect; and not only this, but if a person makes contact with the outside covering of one cable and with earth, or with the outside coverings of both cables, a current may flow through his body. The necessary conditions for the passage of a current, when such contacts are made, always exist to a greater or less degree; but it is only when high pressures are used, in conjunction with cables having an appreciable electrostatic capacity, that the current which may pass is of sufficient magnitude to require consideration.

Let us suppose that there are two perfectly insulated conductors, each of capacity K, between which there is maintained a continuous pressure V. The difference of potential between each conductor and the earth will be $\frac{V}{2}$, and each conductor will be charged with a quantity of electricity equal to $\frac{KV}{2}$. If a contact is made between one of these conductors and the earth, there will be a rearrangement of potentials; with the result that the conductor, with which contact is made, will be at the same potential as the earth, whilst between the other and earth there will be a difference of potential V; and a current of electricity will flow through the conducting medium connecting the conductor to earth. The quantity of electricity to be transferred is the charge on the one conductor plus the

additional charge required to raise the potential of the other to V; and since each of them is equal to $\frac{KV}{2}$, the total quantity which will pass will be KV. The current flowing will have a maximum value of $\frac{V}{2R}$, if R is the resistance of the contact, and will rapidly diminish in value as the difference of potential between the earth and the conductor is reduced; so that the shock received by any person making such a contact may be very sharp if V is high, but will only last for a short time.

The case is somewhat different, however, with alternating currents, as the charge is not a steady one, owing to the continual variation of the value of the instantaneous difference of potential. When a condenser of capacity K has its plates connected to the terminals of a dynamo, or transformer, supplying an alternating current at a pressure V, and a frequency n, a current is delivered to it which may be measured by the expression $C = \frac{2\pi n KV}{10^6}$, if K be expressed in microfarads, C in amperes, and V in volts. Now any system of cables connected in a circuit is the equivalent of a condenser, or of a combination of condensers; and therefore, if we can determine the capacity of the circuit under any given conditions, we can measure the current which flows across the dielectric. Now consider the case of two insulated cables between which there is a pressure V, and let the conductor of one be connected to earth by any person making simultaneous contact with it and the earth; then, if the capacity of the other cable with respect to earth is K, the condenser current, which will flow through the body of the person making connection, will be equal to $\frac{2\pi n KV}{10^6}$.

This current may be of considerable magnitude, if the cable is long and laid underground, so that its capacity is large; for example, with a capacity of half a microfarad and a pressure of 2,000 volts at a frequency of 80, the current would be half an ampere. With an overhead cable of the same length the capacity would be much smaller, and the current, which would pass through the body of any person making contact with one conductor and with the earth, would be proportionately less; but it might still be sufficient to give a very unpleasant shock.

For similar reasons a current will pass through the body of any person making contact with the outside of the insulating covering of one cable and with earth, or with the outsides of both cables, always supposing that the outside of the dielectric is not already connected to earth through a low resistance. This is a matter of some importance with overhead cables which are carried on insulators; as, if they are sheathed with metal, or if the tapes or braiding which cover the dielectric are wet and therefore fair conductors, it is possible to get a shock by making contact with them. The current, which will pass under such conditions, may be calculated when the joint capacity of the cables is known; for instance, if there are two overhead cables, each having a capacity K as measured between their conductors and outside sheathing or braiding, and K′ as measured between their conductors and earth, their joint capacity, when the sheathing of one is connected to earth by any person making contact with it, is $\frac{KK'}{K+K'}$, since they are equivalent to two condensers joined in series; and the condenser current will therefore be equal to $\frac{2\pi n VKK'}{10^6(K+K')}$. When the two sheathings are

connected by any one making contact with both of them, the two capacities joined in series are equal, each being K; and the joint capacity is equal to $\frac{K^2}{2K} = \frac{K}{2}$ If now the pressure is 2,000 volts, the frequency 80, and the values of K and K′ respectively ·5 and ·015 of a microfarad, figures which may fairly represent the state of affairs on a high pressure main one mile long, we find that $\frac{2\pi n V K K'}{10^6 (K + K')} = \cdot 0145$, and that $\frac{2\pi n V K}{10^6 \times 2} = \cdot 25$; that is, that a current of $14\frac{1}{2}$ milliamperes would pass through the body of any person making contact with the sheathing of one cable and with earth; and a current of 250 milliamperes, or a quarter of an ampere, would pass when the contact is made between the sheathings of the two cables. When the outside of the cable is connected to earth at all times, as is the case with underground cables, or with overhead cables when not attached to insulators, this condenser current will have an easier path than through the body of any person making contact with the sheathing; and it is therefore advisable to connect to earth the outside protective covering of all overhead cables, as also any bearer wires which may be used to support them. This will no doubt increase the current flowing, when contact is made between a conductor and earth, because it increases the capacity of the cables; but it is so much easier to guard against an accidental contact with the conductor, by properly protecting all terminal connections, that this is of a secondary importance. The Board of Trade Regulations specify that, if the protection afforded to the dielectric be wholly or partly metallic, it shall be efficiently connected with earth; and, although it is not specified that the suspending wires of overhead lines shall be so connected, the

advisability of so doing appears to be recognised, as the clause in the old regulations which stipulated that the suspending wires should be in contact at the supports only with insulating material finds no place in the new rules.

When high pressures are used, the possibility of a disruptive discharge from one conductor to another, or from either to earth, has to be considered; and the conditions, which determine whether such a discharge will take place or not, do not depend on the actual insulation resistance, but on the distance apart of the two bodies between which the difference of pressure exists, and on the power of the intervening material of withstanding the strain set up in it. In this respect air is of all insulating materials the least efficient, a pressure of 10,000 volts alternating being able to break down the resistance offered by an air gap of six-tenths of an inch between a plate and a point; but if resin oil is used instead of air, the distance that can be sparked across with the same pressure is reduced to about one-tenth of an inch.

The resistance opposed by solid insulators to a discharge is also much greater, and can best be measured by clamping a sheet of the material between two metal discs, and connecting these discs to the two terminals of the transformer or induction coil. When tried in this way, the author has seen sheets of indiarubber and gutta percha between 30 and 40 mils thick resist a pressure of 20,000 volts; and in some tests which he has made on rubber and gutta-percha covered wires of ordinary stock sizes, the following results were obtained :—

Of five wires, conductor 28 mils covered with rubber to a thickness of 28 mils, three broke down at 5,200 volts, and two at 6,200 volts; and with wires 36 mils

diameter covered with rubber to a thickness of 36 mils, one broke down at 7,900 volts, and four at 8,400 volts. Out of a similar number of wires of 48 mils diameter covered with gutta percha to a thickness of 28 mils, one broke down at 8,200 volts, which was the highest pressure which could be obtained from the transformer in use at the time, and the others withstood this voltage for an hour and a half without failing. With thicker coverings the pressure required to break down the dielectric will probably increase rather faster than the thickness, until it reaches something like 60 mils or thereabouts, as the difficulty of making the core perfect mechanically is greater with very thin coatings of insulating material, and the discharge takes place at some weak spot in the dielectric at a lower pressure than that which would be required to pierce a perfectly even sheet of the same thickness.

CHAPTER VIII.

Continuously Insulated Cables.—Requirements of Good Insulating Materials.—Importance of Durability and Permanence.—Resistance to Disruptive Strain.—Thickness of Insulating Covering.—India-rubber.—Gutta Percha.—Bitite.—Fibrous Insulating Materials.—Lead Encased Cables.—Concentric Cables.—Sheathed Cables.—Rise of Pressure and Condenser Current in Ferranti Mains.

Of the two methods of insulating conductors to which reference was made in the preceding chapter, the one which is most frequently employed is that in which the conductor is covered along its whole length with a continuous envelope of insulating material. The core thus made is then covered with a protective coating of tapes, or braiding, or with a metallic sheathing, and is then called a cable.

Many different materials are employed as the insulating medium, each having its advantages and disadvantages, and each possessing, to a greater or less degree, those qualities which are essential to the production of satisfactory working. These qualities vary according to the nature of the work which the cable is called on to perform; but in all cases it is necessary that the material, or combination of materials with which the conductor is covered, should provide a fairly high insulation; and that the resistance opposed by it to the passage of a current should remain constant within small limits under all the varying conditions of working In order that this may be so, the insulating covering must be waterproof, as moisture penetrating into it will at once cause a leakage of current; it must be mechanically strong and tough, so that it cannot

easily be torn or split; it must be flexible, so that it can be bent without cracking; it must be capable of withstanding fairly high temperatures without softening, or being in any way permanently injured; and it should be unaffected by the acids or gases with which it may come in contact. In addition to its insulating qualities it must, when used for high pressure work, be capable of offering great resistance to disruptive discharge; and to this end the material should be homogeneous. When these requirements are fulfilled, the best cable is that whose cost, bulk, and weight are least, and which can be most easily fixed in place and jointed.

As regards insulation, we have seen that the resistance of a cable per unit length depends on the thickness of the covering, and on the specific insulation resistance of the material employed, and it is therefore important that the value of this specific resistance should be high. Too much stress must not, however, be laid on the necessity of very high initial resistance; as it is better to have a medium value for this, if that value is permanent, than to start with a high resistance which is likely to be soon lowered by the strains to which the cable is subjected in ordinary working. In many cases, such as in the internal wiring of buildings or ships, the insulating covering of the cable is so much cut about for the making of joints and connections to switches, lamps, and other fittings, and so many of these latter are connected in the circuit, that the insulation resistance of the complete installation is determined chiefly by the resistance of these fittings to surface leakage; and is affected to a very slight degree by the insulation resistance of the cable itself. For instance, in an installation of 100 incandescent lamps, there will be at least 300 places where the cables are connected to

fittings of one kind or another; each of which affords an opportunity for leakage over the surface of its insulating base. Now if the resistance at each of these places is as much as 300 megohms, the joint resistance is only one megohm; and the difference that will be made by adding the leakage from the uncut parts of the cable will be very small, with the average length of wire in such an installation, whether its insulation resistance is 50 or 1,000 megohms per mile.

Although from this point of view it may appear unnecessary to use cables of high insulation resistance, there are many reasons why they should be used in preference to those having a low resistance; since, as a general rule, a cable of high resistance is more easy to manufacture with uniformity, and offers to the manufacturer a better chance of discovering by the insulation test any partial fault which may exist in it; and further, in any installation, where cables are employed whose normal insulation resistance is high, it is easier to discover and localize a fault, than if the insulation of the cables used gives a low resistance.

Uniformity of specific resistance is of great value to the manufacturer, who tests his cables, not only with a view to their passing some guaranteed standard, but as a check on the manner in which their manufacture has been carried out; as it enables him to calculate, from the known dimensions of the cable, what the resistance should be: and by comparing the measured with the calculated resistance, he can detect the existence of any flaw in the covering, or difference in the quality of the material, which, although it does not reduce the resistance below his guaranteed standard, will in time cause the failure of the cable.

The power of withstanding the breaking-down strain of a high pressure is of equal, if not greater importance

than high insulation resistance, in cables which will be subjected to such strains; and, as we have already seen, these two requirements do not always go hand-in-hand. For instance, air is a most perfect insulator, in fact its insulation resistance is so high as to be practically unmeasurable; but it is also the dielectric which is least able to withstand the disruptive strain of a high electric pressure: and although the difference is not so marked, there are with such materials as rubber, gutta percha, and ebonite, many qualities which, although they have a higher specific resistance than others, are yet less able than them to withstand disruptive strain.

When we consider cables insulated with the same material, but having conductors of different diameters, we find the same thing; since, to make the insulation resistances equal, we must keep the ratio of the outside to inside diameter of the insulating sleeve constant; that is, we must increase the thickness of dielectric in the same proportion as the diameter of the conductor; whereas to obtain the same power of resisting disruptive discharge with a larger conductor does not require any increase of thickness of dielectric: indeed, theory indicates that a given thickness of dielectric on a large conductor should resist a greater pressure than the same thickness on a small conductor. This apparently anomalous result is explained by the fact that the fall of potential from the inside to the outside of the dielectric will not be at the same rate throughout the thickness, but will be, for any thin layer, proportional to the resistance of that layer; and that is, as we have already shown, proportional to $\log \frac{D}{d}$ when D and d are respectively the outside and inside diameters of the layer under consideration.

If then, we examine the case of a thin layer next

the conductor of thickness t, and suppose that a difference of potential V is maintained between the conductor and the outside of the insulated core, and that the total thickness of dielectric is T; we find that the difference of potential V′ between the inner and outer surfaces of this thin layer may be calculated from the equation $\frac{V'}{V} = \frac{\log \frac{d+2t}{d}}{\log \frac{d+2T}{d}}$.

Take, as an example, two conductors of 0·1 inch and 0·5 inch diameter, each covered to a thickness T of 0·1 inch and subjected to a pressure V of 2000 volts, and let us find the value of V′ for a layer of insulating material of 0·01 inch thick next the conductor.

$$\text{If } d = 0{\cdot}1 \quad V' = 2000 \times \frac{\log 1{\cdot}2}{\log 3} = 332$$

$$\text{If } d = 0{\cdot}5 \quad V' = 2000 \times \frac{\log 1{\cdot}04}{\log 1{\cdot}4} = 233$$

which shows that with the smaller conductor the innermost layer of dielectric is subjected to a pressure more than 40 per cent. greater than is the case with the larger conductor.

There are then three separate points which must be taken into consideration in determining the proper thickness of insulating material, viz.:—the prevention of leakage, of disruptive discharge, and of mechanical injury to the dielectric. For conductors of different diameters insulated for equal resistances with the same material, the thickness of the dielectric must be increased in proportion to the diameter of the conductor: for equal resistance to disruptive strain, the

thickness of the dielectric need not certainly be increased if the diameter of the conductor is increased: and lastly, for mechanical strength the thickness must be increased as the conductor is made larger; but in this case, it is not found necessary to increase it in proportion to the diameter. The question then arises as to what is the best rule to work on in deciding the amount of any insulating material that should be used; and this must necessarily depend on the material, and on the conditions of working. With dielectrics which have a high specific resistance, the thickness is generally settled by considerations of mechanical strength when low pressures only are to be used; as in this case, the insulation resistance will probably be ample with any thickness which is practicable. When high pressures are to be used, the same consideration will be the important one with large conductors; but with small ones, it will be the thickness required to resist the breaking-down strain due to the high pressure. With materials of low specific resistance, the thickness required for insulation resistance becomes more important, and may, except for very small conductors, outweigh all other considerations; and with materials which are not homogeneous, and in which air passages may exist, the prevention of disruptive discharge due to high pressures is the most difficult matter to deal with.

An examination of the thicknesses of dielectric stated in the lists of various makers of vulcanized rubber cables shows that, for the smaller cables and wires used in indoor work, the thickness which has been found satisfactory in practical use may be represented very closely by the formula $t = 0{\cdot}1d + 0{\cdot}032$, all dimensions being in inches. For larger cables, such as are used for low tension underground mains, a close

approximation is given by $t=0{\cdot}09d+0{\cdot}040$; and, as large quantities of such cable have been in use for years underground with satisfactory results, it may fairly be assumed that the thickness of dielectric calculated from this formula is sufficient to give the required mechanical resistance when good quality rubber is employed.

Coming now to cables for use with high pressures, we find that makers seem to work more nearly to a constant value of $\frac{D}{d}$, so as to maintain a very high insulation resistance even for the largest conductors, that is to say that the multiplier of d is larger; but this would appear to be quite unnecessary, as sufficient mechanical strength and electrical resistance would be obtained by using the formula $t= {\cdot}09d+0{\cdot}040$ given above. It would, however, be necessary to fix a minimum thickness, which should be sufficient to prevent the breaking down of the dielectric by a disruptive discharge, and to abandon the use of the formula when it gave a smaller value of t.

This minimum thickness of dielectric has been fixed by the Board of Trade Regulations, which require that no high pressure cable shall have a less thickness of delectric than $\frac{1}{10}$th inch, and that if the working pressure exceeds 2000 volts, the thickness of dielectric expressed in inches shall not be less than the number representing the working pressure in volts divided by 20,000.

The continuously insulated conductors, which are in use at present, all belong to one or other of two main classes; in one of which the dielectric material is unaffected by the presence of moisture, being a homogeneous mass whose power of absorbing water is very small; whilst in the other the dielectric material must

be supplemented by a watertight metallic envelope, since it is composed of fibrous material which absorbs water readily. The materials used to insulate cables of the first class are india-rubber, either by itself or mixed with other materials, gutta percha, and a preparation of bitumen which has been called bitite; whilst for cables of the second class, jute, hemp, cotton, or paper impregnated with oils, waxes, or bituminous and resinous compounds, are usually employed.

Of these materials, the one which is best adapted to withstand the strains to which an electric light cable is subjected is india-rubber, when of good quality and properly applied; as its specific resistance is high, and its power of withstanding the strains due to high pressure greater than that of almost any other insulator, either solid or liquid; and, further, it is thoroughly waterproof, capable of standing changes of temperature over a wide range without injury, and mechanically strong, tough, and flexible. So far as the comparatively short time during which insulated cables have been in use for electric light mains will allow us to judge, vulcanized rubber cables are also the most durable. There were very few public supply stations distributing current before 1890, but rubber cables were laid underground for private installations as far back as 1883, and have given satisfactory results. Rubber cables have also been in use with satisfactory results for ten years or more on the circuits of the Eastbourne, Hastings, London Electric, Metropolitan, House to House, and Newcastle Companies, all of which work with high-pressure systems, besides having been largely used on low-pressure circuits, and for house and ship wiring from the earliest days of electric lighting.

India-rubber has, however, one great disadvantage

which is, that it is expensive; and it is on this score that objection is often raised to its use; but, if this is left out of consideration, and the matter looked at entirely from the technical point of view, there is no doubt that rubber cables are the best, so far as our present experience goes. The first cost of the cable is, however, a serious matter, and must naturally engage the attention of all engineers; since the most economical cable should be chosen on lines similar to those which determine the economical area of the conductor; that is, that cable should be used, for which the sum of the interest on capital outlay and of the cost of maintenance and depreciation is a minimum. This is a problem for which the complete data cannot be furnished for some years to come, and for the present therefore it cannot be discussed further.

Gutta percha, although excellently well suited to the requirements of submarine telegraphy, is unsatisfactory on account of the low temperature at which it softens, and it has therefore been very seldom employed as an insulator for electric light work, where heavy conductors and large currents are required. It further has the disadvantage that, when exposed to the atmosphere, it becomes brittle and cracks. If kept under water at a temperature between 40° and 80° Fahr., it is an excellent insulating material; and, when protected by a good covering of tapes and Stockholm tar, and laid underground where it can be kept at a fairly constant temperature in a moist atmosphere, it gives satisfactory results in telegraph and telephone work. For electric light cables it has been sometimes used under water, or in very damp places; and at the Great Western Railway installation it has been used for the underground mains; but unless under water, the sectional area of the conductor must be increased

so as to prevent any appreciable heating, as otherwise the conductor is liable to sink through the insulation and destroy the cable.

Bitite, the insulating material used by the Callender Company, is a preparation of bitumen; and much difficulty was at one time experienced in preparing it so that it was neither so hard and brittle as to crack when bent, nor so soft as to allow of the conductor becoming uncentred. This difficulty has now been overcome, as samples cut off cables which have been in use for a considerable time show no signs of decentralization. Electrically, its specific resistance is not very high, and it does not appear to stand the strains due to high pressures so well as many other insulating materials; so that its use has been confined chiefly to low-pressure installations. Bitite cables are often further protected by being laid in troughs, which are filled up solid with a bituminous compound, and this treatment of them appears to give the most satisfactory results.

Two new insulating compounds have quite recently been introduced: one by Messrs. Glover, and a second by Messrs. Siemens, both of which are said to be waterproof and to withstand very high electrical pressures; but neither of them has as yet had an opportunity of proving its durability by continued use for any length of time.

The cables of the second class, which are most generally used, are those in which the conductor is covered with cotton, jute, or paper, impregnated with an insulating compound, and the whole enclosed in a lead tube. Cables made in this way are, as a general rule, considerably cheaper than good rubber cables; but they have, in the author's opinion, various disadvantages, which render them inferior from both a

mechanical and an electrical point of view; and it must therefore be a question for the engineer to decide in each case as to whether the more expensive cable is worth its price to him or not.

The insulation resistance of these lead-encased cables depends on the complete expulsion of all moisture from the fibrous material before it is surrounded with lead, and then on the lead casing as a means of preventing fresh moisture from being absorbed. Now, it is well known that the continual application of heat to a fibrous material has the effect of taking all the strength out of the fibre; and there is therefore great danger, either that the moisture will not be expelled sufficiently, or that the fibre will be unduly weakened. The varying amount of moisture in the fibrous material, before it is immersed in the bath of compound, prevents a uniform treatment from giving equal insulation resistances for cables of similar dimensions; and this makes it more difficult to decide whether an insulation resistance which is below the average is due to a local fault or to a uniformly lower specific resistance; thus taking away considerably from the usefulness of the insulation test.

The hygroscopic nature of the insulating material makes it ready to absorb moisture again, whenever it is exposed to the air; and great precautions must therefore be taken, when making joints or terminating a cable, to prevent this absorption from taking place, as otherwise the insulation resistance will be lowered. From the same cause any small flaw in the lead will sooner or later make a fault; and it is very difficult to ensure that the lead casing is perfect even when it leaves the factory, as the flaw may be so small that the lowering of the insulation is hardly appreciable, until after the lapse of a much longer time than that

during which the cable is under test in water. There is also the further danger that the lead may be damaged during the process of laying the cable, or that when laid it may be destroyed by chemical action.

The durability of lead pipes is very variable when laid in the soil; and although we sometimes hear of short lengths of lead pipe, or of some of the early lead-covered telegraphic wires, being dug up and found to be in excellent condition, we seldom hear of any long length which has remained perfect; and experience has unfortunately shown us that under certain conditions the effect of chemical action is very rapid. A striking instance of this is the rapid failure of many cables covered with pure lead, and laid in creosoted wood conduits, which has caused so much trouble in America; but in this particular case, a partial remedy has been found in alloying the lead with a small percentage of tin, which has given much better results.

As regards the resistance to disruptive discharge, the fact that the dielectric is not homogeneous, and that the component parts have different rates of expansion and contraction, causes cracks and small air paths in the insulation, and these offer a much lower resistance to the discharge. This has been a great source of trouble on arc light circuits in America, and it has been found necessary, on account of the frequent occurrence of faults, to increase the thickness of the dielectric very considerably, making it first $\frac{5}{32}$ of an inch instead of $\frac{3}{32}$ of an inch, and finally $\frac{3}{16}$ or $\frac{1}{4}$ of an inch, which has now become an ordinary thickness.

Notwithstanding these disadvantages, the lead-encased fibrous cable has been extensively employed on account of its lesser cost, more especially for low pressure distribution; but the cotton- or jute-covered cable has, in great measure, given way to paper, which,

whilst suffering from the same disadvantages due to its hygroscopic nature and entire dependence on the lead covering for retaining its insulation, has the merit of offering a greater resistance to disruptive discharge owing to the covering being built up of a large number of layers of paper.

When considering the relative advantages of the various shapes which might be given to the conductor, (see Chapter VI.) we pointed out that the cost of insulation was considerably affected by varying the shape; and that, in many cases, the economy in the weight of the conductor, obtained by using a tubular or rectangular form, was more than counterbalanced by the increased cost of insulation. If the same insulation resistance per mile is required, the weight of insulating material increases in proportion to the square of the surface to be covered per unit length of the conductor, and any increase in the amount of surface has therefore a very decided effect in augmenting the price. This follows from the fact that the ratio $\frac{D}{d}$ of the outside and inside diameters of the dielectric is a constant for equal resistances; and that the weight of the dielectric is proportional to $D^2 - d^2 = d^2 \left\{\left(\frac{D}{d}\right)^2 - 1\right\}$, that is, is proportional to d^2. This has an important bearing on the cost of concentric cables, whose outer conductor is insulated from earth; since the surface to be covered is so much greater. For example, suppose that we wish to replace two separate cables by a concentric cable, and that the same resistances are required in the latter as in the former, both between one conductor and the other, and between either conductor and the earth. If d is the diameter of the conductor, and a ratio $\frac{D}{d} = 2$

gives the desired resistance R_i, the weight of the dielectric, being proportional to $D^2 - d^2$, is equal say to $3\ Ad^2$, when A is a constant depending on the length of the cable and the specific gravity of the insulating material. The weight of the dielectric in the two cables will therefore be $6\ Ad^2$, the resistance between the two conductors $2\ R_i$, and between either and earth R_i. Now compare this with the concentric cable; first, the ratio of $\frac{D_1}{d}$ for the inner insulation must have a bigger value, which may be calculated thus:—

$$\log \frac{D_1}{d} : \log \frac{D}{d} = 2\ R_i : R_i, \text{ and since } \frac{D}{d} = 2$$

$$\log \frac{D_1}{d} = 2 \log 2, \text{ or } \frac{D_1}{d} = 4.$$

The weight is equal to $A\ (D_1^2 - d^2) = 15\ Ad^2$, or five times what it was before. If we consider the outer conductor as a tube of equal area to the inner conductor, and call its outer diameter d_1, we get $d_1^2 - D_1^2 = d^2$ or $d_1 = 4{\cdot}12d$. Now to get a resistance R_i from earth, the outer diameter of the dielectric $D_2 = 2d_1 = 8{\cdot}24d$, and the weight $= Ad^2\ \{(8{\cdot}24)^2 - (4{\cdot}12)^2\} = 50{\cdot}9\ Ad^2$. The total weight of the dielectric in the concentric cable is thus equal to $65{\cdot}9\ Ad^2$, or nearly eleven times the weight of insulating material in the two single cables.

No concentric cables are actually made to give equal insulation resistances, on account of the enormous expense which would be incurred, but it is often necessary to make them with the same resistance to disruptive strain; that is to say, to make the thickness of the dielectric proportional to the difference of potential at its two surfaces; and although in this case one does not find such an enormous difference in the weights of the insulating material, yet the weight in the concentric

cable is often two or three times that in the two separate cables.

The relative merits of concentric, as compared with two separate cables have attracted a good deal of attention; the former being advocated especially for use with high pressure alternating currents. There is a good deal to be said on both sides of the question, and various points have to be taken into consideration. The concentric cable has certain advantages as regards the question of induced currents in neighbouring wires; since, so long as the insulation is good, the inductive effect on a neighbouring wire is nil, owing to the one conductor being concentric with, and entirely enclosed by the other. This is an important matter when telegraph or telephone wires run parallel with and close to a circuit carrying alternating currents; but, so far as the author is aware, no trouble has been experienced in this respect, when two separate cables have been laid close together, as for instance when drawn into the same pipe.

In the matter of safety to the public, the concentric cable is better, under certain conditions of working, than two separate ones; since, if the capacity of the outer conductor with regard to the earth is considerable, and the insulation of all parts of the circuit is good, the mean potential of the outer conductor is the same as that of the earth; and the greatest difference that can exist between the two, is that due to the fall of pressure caused by the current flowing in the cable. This state of affairs is however entirely changed if the insulation of any part of the circuit becomes faulty; for example, suppose a fault occurs in some part of the transformer coil, the point at which the leak exists will be brought to the same potential as the earth, so that between the outer con-

ductor and earth there may, under such circumstances, be a considerable difference of potential. It has sometimes happened, when a fault of this kind has occurred, and the outer conductor has been separated from the earth by a thin coating of insulating material, that a discharge has taken place between the two which has broken down the insulation; and the possibility of the occurrence of faults of this kind therefore makes it necessary that the insulation of the outer conductor should be as thick and as good as that between the inner and outer.

To overcome this difficulty, and to ensure that only a small difference of potential can ever exist between the outer conductor and the earth, it has been proposed that they should be electrically connected at some part of the circuit; and this plan has been adopted in many systems employing alternating currents. With two separate cables laid underground, so that their outer coverings are earthed, the danger of receiving a shock is very remote, except when some part of the conductor itself is handled; and this same danger occurs on a circuit in which the cables are concentric, unless the concentric principle is carried right through to all connections to transformers, switches, etc.; that is, unless the inner conductor and all apparatus to which it is connected are entirely enclosed at all points of the circuit within the outer conductor. When this is the case, and the outer conductor is earthed, it is difficult to imagine any arrangement which could give greater safety; but so far, in none of the circuits at present in use has the concentric system been so completely carried out, and therefore the degree of safety obtained by the use of concentric cables is not much greater than that which can be got, when separate cables are used and the ordinary precautions are taken.

A difficulty that is met with in the use of concentric cables is, that it is not possible to ascertain the condition of the insulation between the two conductors, without first disconnecting from them the dynamo, transformers, or other apparatus in the circuit; and therefore one cannot test the insulation when the circuit is working. This is a serious disadvantage of concentric, as compared with separate cables; as, with the latter, a continual test may be kept on the circuit, which will in many cases give warning, before a fault is sufficiently developed to prevent the circuit from being worked, and thus afford an opportunity of localizing and repairing the fault before any interruption of the lighting takes place.

When lead-covered or armoured cables are used for alternating currents, it is always better to use concentric cables; as, when a single conductor cable sheathed with metal is used, there is an appreciable drop of pressure from the induced currents in the sheathing; whereas this drop does not occur with concentric cables, owing to the equal and opposite currents in the two conductors neutralizing one another's effect. M. Ch. Jacquin has published the results of some experiments, in which he compared the fall of pressure in sending an alternating current, whose frequency was 50, through an armoured cable, with that which occurred when sending through the same cable an equal steady continuous current. He found that, if the sheathing was well insulated, the fall of pressure was 18 per cent. greater for the alternating than for the continuous current, and that if the sheathing was uninsulated, which is generally the case, this figure was increased to 28 per cent. When a higher frequency is used, this increased loss in transmission becomes greater, and may add as much as 50 per cent. to the loss in the conductor.

In the matter of jointing, greater difficulty is experienced with concentric than with single conductor cables, especially with T-joints; and, for this reason, the connections are more often made in a special joint box in preference to making the usual soldered and insulated joint.

Before leaving the subject of concentric cables, we may mention two effects, due to their capacity, which have been more especially noticed in the long concentric mains laid by Mr. Ferranti from Deptford to London, viz., that there is, under certain conditions, a very appreciable increase of pressure at both the primary and secondary terminals of a step-up transformer, when connected to these mains, above that which exists when the secondary circuit of the transformer is disconnected from them; and that a current of considerable magnitude flows across the dielectric between the inner and outer conductors. Dr. Fleming has given the results of some experiments on these mains in his paper "On some effects of alternating current flow in circuits having capacity and self-induction." When current was supplied by a step-up transformer to the mains at a pressure of about 10,000 volts, and a frequency of 67, it was found that the ratio of the pressures at the secondary and primary terminals was greater than the multiplying ratio of the transformer coils, by an amount equal to about 5 per cent. when a current of 30 ampères was delivered into the mains, and to from 10 to 15 per cent. when the circuit was unloaded: further, that a current of nearly 16 ampères entered the main, when none was delivered to the transformers at the far end; and that, when 30 ampères were delivered at the far end, the current entering the main was from 10 to 15 per cent. greater. This current is the resultant of the current delivered

at the far end of the main, and the condenser current, which differs 90° in phase from it; and the latter may therefore be calculated by taking the square root of the difference of the squares of the in-going and out-going currents. The condenser current in any cable may, as we have already seen, be calculated independently when the capacity, pressure, and frequency are known, being equal to $\frac{2\pi\, n\, \mathrm{K}\, \mathrm{V}}{10^6}$ where

n is the frequency,
K the capacity in microfarads,
V the pressure in volts.

Of course these phenomena may also occur with two separate cables; but they are not as a rule so marked, owing to the fact that the capacity is not so great. The length of main experimented on, when the results quoted above were obtained, was 11½ miles, and the capacity between the inner and outer conductor for this length was 4 microfarads, when measured by the ordinary steady charge method; this latter figure being somewhat greater than the capacity as calculated from the condenser current by the formula given above

CHAPTER IX.

India-rubber.—Whence Obtained.—Method of Collecting.—Pure Rubber.—Vulcanized Rubber.—Pure Rubber Cables.—Compound Rubber Cables.—Vulcanized Rubber Cables.—Joints in Rubber Cables.—Okonite.—Gutta Percha.—Joints in Gutta Percha Cables.—Bitite.—Joints in Bitite Cables.

India-rubber, which is extensively used for the continuous insulation of electrical conductors, is a gum obtained from a milky sap, existing in the middle layers of the bark of certain trees and creepers, which grow in various parts of South America, Africa, and the East Indies. It is obtained by making incisions in the bark, or by stripping off the outer layer of it; or, as is often done on account of the larger immediate yield, by cutting down the trees; and the sap which exudes is collected, and treated in different ways to make it coagulate. The quality of the gums received from different districts varies very much, the variation being partly dependent on the tree from which it is obtained, and partly on the method of collection and the after treatment it receives at the hands of the natives.

The best quality of rubber is that obtained from Para, after which may be placed the East Indian, Central American, and African, in the order named; and much of the superiority of Para rubber is attributed to the more careful way of collecting it, and to the method of coagulating the milk, by exposing it in thin layers to the smoke of a fire made of wood and certain native nuts. This treatment appears in great measure to neutralize the effect of a decomposing agent, which exists in the gum as collected from the trees, and acts so rapidly, that much of the rubber, which is not so

well dried, arrives in England in a partially rotten state.

The best qualities of Para rubber in the raw state have great tensile strength and elasticity, and are not nearly so liable to decompose as after they have undergone the processes of washing and mastication; but, unfortunately, the raw rubber cannot be easily applied to the various purposes for which it is required; and for convenience in handling, and to remove the impurities often found mixed with it, it is necessary to submit it to the processes of washing and mastication, in which the rubber is broken up, and its strength and elasticity destroyed to a great extent. The masticated rubber may be made into sheets and strips, and it is in this latter form of strips wound spirally round the conductor that the pure rubber is used for insulating purposes. Pure strip made from the best qualities of raw rubber has a high specific insulation resistance, but it is very susceptible to changes of temperature; and the application of only a moderate heat hastens the decomposition of the rubber, which is due to some solvent agent contained within itself, and which causes it, when exposed to light and the action of the atmosphere, to become viscid, and afterwards to assume the form of a brittle resin.

All the conductors used for telegraphic work in the early days, when insulated with rubber, were covered with spiral wrappings of tape, the overlapping strips being joined together by the use of naphtha, or by the application of heat. This treatment, although it made the insulating covering fairly watertight, helped on the early decomposition of the rubber; and it was this rotting of the rubber which was the chief cause of the preference accorded to gutta percha; a preference which still appears to exist, although certainly without any

adequate reason, so far as land telegraph work is concerned, now that such improved results are obtained with vulcanized rubber insulation. The use of vulcanized rubber insulation was proposed nearly forty years ago, and patents were taken out for several methods of covering conductors with a coating of this material; but it was not until 1868 and the following years that it was used to any great extent. Since that time several thousand knots of submarine cable, with vulcanized rubber core, have been laid, much of which is still working, after being more than twenty years under the sea.

So far as electric lighting is concerned, it is only since 1887 that this class of cable has been at all extensively employed, although small quantities were occasionally used for special work before this time; but now it is recognised as one of the best, if not the best, material for the insulating covering of cables and wires, more especially when currents are distributed at high pressures, and great strains are therefore put on the dielectric. In this connection we may quote the opinion expressed by Herr Kopsel, as the result of experiments with high pressures carried out in 1891 at the works of Messrs. Siemens and Halske, at Charlottenburg, which was, that the only possible solid insulator for high pressure work was specially prepared vulcanized india-rubber.

On account chiefly of the simple machinery required and the ease of manufacture, cables and wires insulated with pure rubber strip were almost universally employed in the earlier days of electric light work; and many hundreds of miles of such wires were fitted up in houses and other buildings, and on board ship. The conductor was, as a rule, wrapped first with cotton thread, and over this one or more layers of pure

rubber strip were laid on spirally, the core thus formed being afterwards taped and braided. The objections to this kind of insulation are, that the covering is not waterproof unless the strips are made to stick together by the use of a solvent, or by the application of heat; and both these methods are harmful to the rubber: that it does not stand either very low or very high temperatures without injury: and that the covering has not sufficient mechanical strength to allow of the wire or cable being handled without risk of damage. This want of mechanical strength was felt more especially with the larger cables, which, owing to the great expense of putting on a thick coating of pure rubber, were generally covered to the same thickness only as the small wires.

For these larger cables, therefore, a different method of preparing and applying the rubber was introduced, which allowed of a much thicker covering being put on than was possible, at the same cost, with pure rubber, besides bringing with it other advantages of considerable importance. For this purpose the rubber was thoroughly mixed and kneaded together with pigments such as litharge, French chalk, oxide of zinc, barytes, lamp black, sulphide of lime, etc.; which, although generally lowering the specific insulation resistance, produced a compound rubber a good deal cheaper, volume for volume, than the pure rubber, and one which was stronger mechanically and less liable to decompose, when the rubber and pigments were carefully chosen so as to suit one another, and were thoroughly well mixed. Some of these pigments, especially litharge and French chalk, have a drying effect, and hinder decomposition by absorbing the solvent which is the active agent; whilst others make the compound tougher or harder. The pigments to be used, and the

quantities of each, must therefore be determined with special reference to the quality of the rubber, and the conditions under which it is to be used. The mixed rubber is run out into sheets and cut into strips of suitable width, which are applied to the conductor under considerable pressure, and in such a manner that two longitudinal joints are formed along the whole length, where the strips of rubber are squeezed together. Although these joints are only mechanical, yet if the rubber is in good condition and the edges clean, they are sufficiently good to permit of the cable being used under water. Before being covered with rubber, the conductor is usually wrapped with a prepared tape, and outside the rubber another tape is placed, and the whole is then covered with a strong braiding, and coated with a compound to keep the fibrous covering from rotting.

The advantages of the compound over the pure rubber insulation are that the former makes a practically homogeneous and waterproof covering, which, owing to its greater thickness and strength, will bear rougher handling without injury; and that the compound rubber does not decompose so rapidly, and is affected to a lesser degree by variations of temperature. Cables insulated in this manner have been in use for some years, not only for internal wiring, but also for outdoor work, both overhead and underground, and on circuits working in many instances with high pressures. These cables have given satisfactory results, although in some cases the mechanical joint between the two strips has been a cause of trouble; but the rubber, superior as it is in lasting qualities to the pure strip, is still not in the state in which it is most durable and least affected by variations of temperature.

[illegible] class of rubber cable which is most used at the

present time, is that in which the rubber is vulcanized; and its use in this form, in preference to any other, is justified, not only by the experience already gained with electric cables, but by the fact that almost all manufactured rubber articles are treated in this manner; and that when durability, flexibility, and the capability of withstanding high temperatures are required, the experience of rubber manufacturers has shown them that vulcanized rubber is the best, and indeed, only form of rubber which is thoroughly satisfactory. The process of vulcanization, or curing, is performed by mixing with the rubber a small quantity of sulphur, and by subjecting the mixture to a temperature of from 250° to 300° Fahr. whilst keeping it under pressure. The actual percentage of sulphur required, the temperature, and the length of time during which it is maintained, vary very much with the quality of the rubber used; some rubbers allowing only of a small variation of temperature, whilst others may be vulcanized by being subjected to a temperature as low as 250° or as high as 300°, the time varying perhaps from four or five hours to under one hour. It is therefore very necessary, when vulcanizing joints for instance, that full directions, as to the best temperature and time during which it is to be maintained, should be got from the manufacturer for the particular quality of rubber in use, and also that the permissible limits of variation of temperature and time should be defined, as otherwise there is a risk of either undercuring the rubber, or overcuring or burning it.

By this process of vulcanization the sulphur is made to combine chemically with the rubber, with the result that the action of the decomposing agent is neutralized, and the durability of the rubber immensely increased; and at the same time it is made mechani-

cally stronger, more flexible, and capable of withstanding a higher temperature without injury. The joint between two pieces of rubber, when they have been vulcanized together, is also no longer a mechanical one, but the two pieces are completely joined together into one homogeneous mass; so much so, indeed, that it is not possible by examination to discover the exact position of the joint. The use of sulphur has been objected to by some people on account of its deteriorating effects on the copper wire, but this difficulty may be overcome by tinning the copper wire, and by a proper proportioning of the quantity of sulphur used; that is, by mixing only just so much as will combine chemically with the rubber, so that little or no free sulphur is left which may act on the wire.

A method frequently employed to prevent this action, is to interpose a coat of specially mixed rubber, called technically the separator, between the sulphurized rubber and the conductor; the function of the separator being to combine with any excess of sulphur, and so prevent it from passing through to the copper. One of the early methods, proposed by Hooper for using vulcanized rubber as an insulator, consisted in first covering the conductor with pure rubber, then putting on a thin metal covering, and over this the vulcanizing rubber; but in the cables actually made by him, the metal covering was replaced by a layer of rubber highly pigmented with oxide of zinc, and this form of separator continues to be extensively used at the present time. There is, however, very little need for the use of a special separator, which is often inferior in mechanical and electrical qualities to the vulcanized rubber proper; since the right amount of sulphur can be so nearly determined, that the quantity of it left free, after vulcanizing, may be made infinitesimally

small, and its action on the wire, if any, may be reduced to a slight tarnishing of the exterior surface.

The method of insulating the conductor, which is most generally adopted at the present time, is to first wrap round it one or more layers of pure rubber tape, which are put on spirally; the direction of the spiral being reversed for each successive layer. On the top of this the compound rubber is applied in two or more separate coatings, each coat being put on by passing the partially formed core with two strips of compound rubber, one above and one below it, between a pair of rollers, which fold each strip half round the core, and firmly press together the edges of the upper and lower strips in such a manner as to make a good longitudinal joint along each side. When a sufficient number of layers of compound rubber has been put on to give the requisite thickness, the core is tightly bound with a spiral wrapping of prepared rubber tape, and is then ready for vulcanizing. The object of putting the compound rubber on in several separate layers is, to render it practically impossible for any weak place in the rubber to extend right through the covering; as, if we suppose that in any given length there is one faulty place in each coating, it is extremely improbable that they should all occur at the same point. Another reason is, that the longitudinal joints are better made with a number of comparatively thin layers, and the soundness of these joints is, as will be readily understood, most important. In order that the several layers, as many as eight or ten being put on some heavily insulated cables, should adhere together, and that the longitudinal seams should be well made, it is necessary that the surfaces of the rubber should be absolutely clean and free from grease of any kind; and the successful manufacture of these cables depends, to a very

great extent, therefore, on the careful handling of the rubber.

The pure rubber may be replaced by a layer of prepared tape, which very effectively keeps the copper clean, although it does not add to the resistance like the pure rubber, or such a tape may be put on before the pure rubber is applied; and, of the coatings of compound rubber, some may be of a separator, and some of a sulphurized rubber, or all may be of one quality. When ready for vulcanizing, the core is coiled on drums which are put into a steam chest; or, for larger sizes which cannot conveniently be so treated, the core is coiled in layers in large iron tanks, the layers being supported, and separated from one another, by being embedded in chalk or other similar material. The core is then kept at the proper temperature for such a time as is best suited to the particular quality of rubber which has been used. When taken from the cure, the core should be immersed in water, and tested for insulation resistance, to see that there are no faults in the covering, and that the resistance is up to the proper standard for the quality of rubber that has been employed; and, if satisfactory, it is then taken to the taping or braiding machines, where the external covering of compounded tapes or braiding is put on.

Although a covering of lead is in no way necessary for insulating purposes with a waterproof material like rubber, these cables are sometimes encased with lead as a further mechanical protection. This may be done by drawing the cable into a lead tube, which is afterwards drawn down through dies, until it fits tightly on the cable; or the lead covering may be put on in a hydraulic press in the manner usually adopted for covering the fibrous insulated cables. When laid in the ground direct, instead of in a pipe or conduit, these cables are sheathed with galvanized iron wires, or

with steel tapes laid on spirally in two layers, so arranged as to break joint.

The methods employed to reinsulate the conductor at places where joints have been made, affect the satisfactory working of the cables and wires to a considerable extent; and of the two methods to be described, the second, in which the rubber is vulcanized, is vastly superior to the first, and should always be used for outdoor work, and on high pressure circuits. The first method, by which the joint is insulated with pure rubber, gives, however, sufficiently good results for all practical purposes, when low pressures are used, and

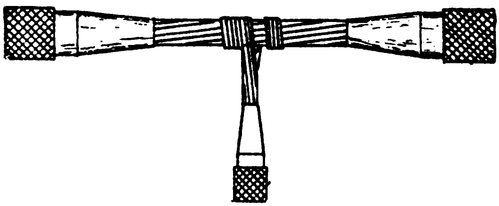

FIG. 32.

the joint is not exposed to high temperatures or much moisture; and, owing to its greater simplicity and cheapness, it is almost universally used for indoor work.

PURE RUBBER JOINT. The copper joint having been made in the manner described on p. 112, and left with a smooth and clean surface, the external tapes and braidings should be stripped back from the rubber, so as to be well clear of the part to be covered with the new insulating material; and the surfaces of the old rubber, which have been exposed during the making of the copper joint, should be cut away, and the rubber, if of sufficient thickness, trimmed down to a long bevel (*see* Fig. 32). The bare part of the conductor, and the

bevelled surfaces of the old rubber should then be lapped tightly and evenly with pure rubber strip, until the diameter becomes equal to, or slightly greater than that of the original core. Strong prepared tapes should then be lapped tightly over the rubber, and, for a short distance, over the original braiding, and the whole well varnished. India-rubber solution is often used to make the adjacent strips of pure rubber adhere to one another; but this is generally unnecessary, if the rubber is clean and is put on with enough tension; in any case the solution should be used very sparingly, and ample time should be allowed for the spirit to evaporate before it is covered by another layer of rubber. The plan of smearing each layer with a quantity of solution, and immediately covering it up with rubber, is one of the surest that can be devised for speedily rotting the rubber. When the thickness of rubber is not sufficient to allow of its being trimmed to a bevel, the pure rubber may be lapped over the outside of the old rubber for say an inch at each end; the surface of the old rubber being first scraped with a knife, and then wiped with pure benzole to free it from grease or dirt.

Vulcanized Rubber Joint. In addition to the tools required for pure rubber joints, the making of a vulcanized joint requires apparatus for maintaining it at a high temperature for a given length of time; and this apparatus must be fairly portable, and must not take up too much space, since it has often to be used in joint boxes of very moderate dimensions. In the factory the rubber is cured by being kept in contact with steam, but the difficulties of arranging a sufficiently portable steam plant have led to the use of a bath of molten sulphur, in which the joint is placed. This bath or cure may consist of a split

T-box (Fig. 33), the two halves of which are flanged, and can be bolted together, having three openings, one at each end and one at one side. The bottom half of the box is provided with a tap, and the top half with a hole through which the sulphur can be introduced; and in which a thermometer can be placed, so that the bulb is in the molten sulphur, whilst the scale projects outside the box. The temperature is maintained by placing one

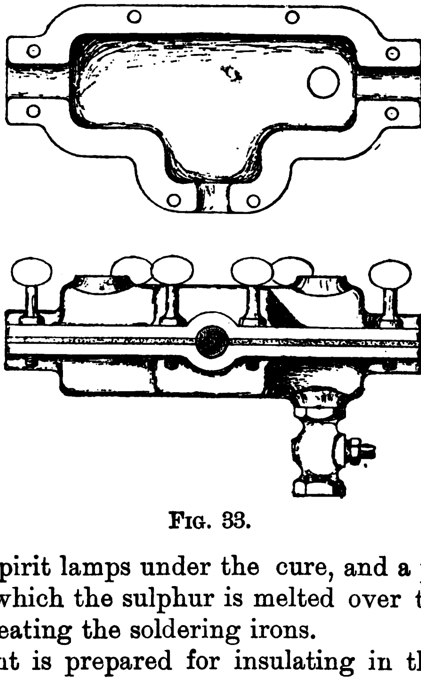

Fig. 33.

or more spirit lamps under the cure, and a pot is provided, in which the sulphur is melted over the firepot used for heating the soldering irons.

The joint is prepared for insulating in the manner already described, and as the cleanness of the bevelled surfaces of the rubber is of the utmost importance, they should be well scraped, and then wiped with pure benzole to free them from dirt or grease. One or more layers of pure rubber are first lapped tightly

round the conductor, and arranged so as just to overlap the inner edges of the old rubber; then, over this and the bevelled surface of the rubber, are lapped layers of vulcanizing rubber, until the diameter of the joint is about equal to that of the original core. The rubber should be put on tightly and evenly, so as to leave no spaces filled with air, and the joint should first be covered with a prepared tape put on spirally, then with a piece of sheeting firmly rolled round it so as to make a longitudinal seam, and finally, it should be tightly bound up with strong selvedge tape applied spirally. The sheeting and selvedge tape are put on to act as a mould, and keep the joint in shape and under pressure, whilst it is being cured, and they are removed again as soon as the vulcanization is completed. The bottom half of the cure is then placed under the cable, so that the joint is wholly within it: the cable is wrapped with common rubber, where it passes through the openings in the cure, so as to protect the original insulation from overheating, and to make tight joints at the openings; the top half of the cure is bolted on, and the molten sulphur poured in. It is advisable to warm the cure before fixing it on the joint, so that the sulphur may not be too much reduced in temperature by the mass of iron in the cure box, as otherwise, it may be difficult to raise the sulphur to the right temperature without a considerable loss of time; and with some rubbers this may cause trouble, owing to the uncertainty which thus arises, as to the proper time to keep them at the full temperature. According to the instructions issued by the Silvertown Company, the rubber they supply for vulcanized joints must be maintained at a temperature between 280° and 300° Fahr. for half an hour at the upper limit, or three-quarters of an hour

at the lower limit, intermediate times being allowed for temperatures between these two; but, if possible, the temperature should always be kept between 290° and 300° Fahr.

At the expiration of the proper time, the molten sulphur is run out through the tap in the bottom of the cure, the cure removed, and the wrappings of selvedge tape and sheeting stripped off. A convenient test of the degree of vulcanization is to try and indent the rubber, when cool, with the thumb nail; if it is properly cured, it will yield to the pressure, but no mark will remain; if the imprint of the nail is left, the rubber is not sufficiently cured; and if it feels hard and unyielding, it is probably overcured. The vulcanized joint is protected externally by lapping it with strong tapes, which should extend an inch or so over the braiding of the cable, and should be well varnished.

With cables insulated with rubber or other waterproof covering, the exclusion of moisture from the ends, where the insulating material has been cut back for making connections to a terminal, is not of such vital importance as in the case of fibrous insulated cables; but it is still advisable to protect the ends. A common plan is to remove the outer tapes and braiding for a few inches and trim the insulating material to a bevel as for making a joint, and then lap the exposed conductor with pure rubber strip which is carried back over the bevelled surface to the tapes or braiding. The author has found it preferable to use strips of vulcanizing rubber instead of pure rubber, and when this has been tightly lapped on, to paint the end with several good coats of anti-sulphuric enamel.

Although the best qualities of rubber cables give most excellent results, it must always be remembered that the rubbers used are in most cases mixtures; and

that, therefore, there may be a very great difference between two cables, both of which are insulated with rubber compounds. For instance, as regards specific resistance, some compounds give ten or more times the resistance of others; and, although there is no absolute rule, it is generally found that the rubber which gives the higher resistance is also that which is the more durable. For this reason it is often necessary to use a cable giving a much higher insulation resistance than is absolutely required for the work, in order that it shall be made of a good quality of rubber, and of sufficient thickness to withstand the mechanical strains to which it may be subjected. Besides those compounds which usually go by the name of rubber, there are others, such as okonite, which are also mixtures of rubber; the special name denoting rather a difference in the process of manufacture than in the material used, as this is varied according to the requirements of each type of cable. One of the leading features in the manufacture of okonite cables, to which great importance is attached in the patent specifications, is the different method of applying the covering; the strip of okonite being laid on a strip of tin foil, and both folded around the wire so that there is only one longitudinal seam; the core also being left enclosed in the tin foil, which is only removed after the okonite has been vulcanized.

Gutta percha, which is so largely used for submarine cable cores and underground telegraph lines, is an insulating material which has met with very little favour for electric light cables, on account of the low temperature at which it softens. The process of manufacture consists in passing the wire to be covered, first through a bath of Chatterton's compound, and then through a press containing gutta percha maintained

in a viscous state by the application of heat; the gutta percha being forced out around the wire, as the latter passes out through a die. The covered wire is then led through troughs of cold water to set the gutta percha, and is coiled on a drum, and taken to be examined; during which process any faulty places in the covering, that may be discovered, are put right by hand. The core is then taken back to the machine, and another coating of gutta percha is put on; and this process is repeated again and again according to the number of coatings required on the wire. The covered wire may then be taped, or drawn into lead tubes, or it may be served with jute and armoured, according to the nature of the mechanical protection which is required.

Joints are insulated in the following manner: The gutta percha is pared back for a couple of inches or so, to remove its outer surface, the wire is covered with Chatterton's compound, and the gutta percha heated on both sides of the joint, and tapered down over it so as to entirely cover the wire. A coating of Chatterton's compound is then put on, and a sheet of gutta percha, previously warmed, is laid over and pressed tightly round the joint, and the excess trimmed off with a pair of scissors. The seam is pressed up tight and finished off with a warm tool, which is worked in such a manner as to mix the gutta percha on both sides of the seam into a homogeneous mass. When cool, the joint is covered with compound, and another sheet of gutta percha is put on and finished off in the same way; and this process may be repeated according to the thickness of the insulating covering.

Bitite, which is the insulating material used by the Callender Company, is said to be bitumen absolutely refined to purity, and vulcanized. The conductor is

covered with a solid sheath of this material, put on in one operation under pressure, and is served with a tape; then covered with insulating compound and again taped, then braided with hemp yarn, and passed through a bath of hot asphalte compound.

Joints in these cables are insulated by wrapping the conductor with bitite, which has been half vulcanized, up to the diameter of the original insulation, and then protecting it by a wrapping of compounded tapes. The joint is then heated by means of a lamp to make the wrappings solid, and to complete the vulcanization of the bitite. Very often, however, mechanical joints are made in special boxes. These boxes have double walls (Fig. 34), through which the cables are passed into the inner box, where the connections are made by means of copper bridges. The space between the inner and outer box is then filled up with bitumen, and the inner

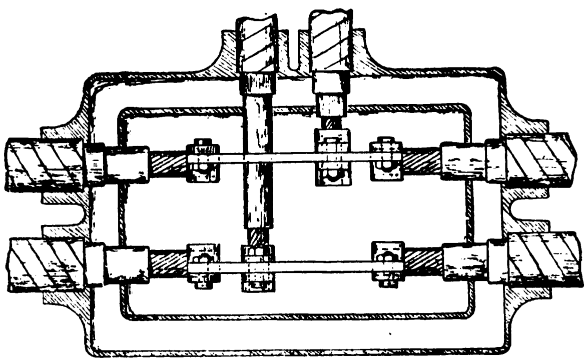

Fig. 34.

box itself with heavy rosin oil, after which a cast-iron lid is bolted on.

CHAPTER X.

Lead-covered Cables.—Early patents.—Methods of Putting on Lead Covering.—Cable Terminals and Joints.—Terminal Boxes.—Joint Boxes.—Edison Tube and Joint Boxes.—Ferranti Concentric Main and Joint.—Brooks' System of Oil Insulation.

THE continuously insulated cables, which have been described in the preceding chapter, although sometimes encased in lead, are not dependent on that covering for the maintenance of their insulation; but there is a type of cable which has been employed a great deal in the last few years, in which the lead covering is not only a mechanical protection, but an integral part of the insulating coating; since it is depended on for the exclusion of moisture from the wrapping of impregnated fibrous material, with which the conductor is surrounded. This type of cable is often spoken of as though it were an invention of recent date, but in reality it was one of the earliest to be tried; indeed, one may say it was the earliest form of cable that showed any signs of being a success. It will be remembered that the first underground wires were insulated with cotton steeped in a resinous compound, and that it was found impossible to keep the lines in working order, owing to damp penetrating through the cotton covering. The immediate result of this was the replacing, wherever possible, of the underground lines by bare wires fixed on insulators overhead; but many of the early workers were strongly impressed with the advantages of an underground wire, and continued, therefore, to search after some

method of overcoming the difficulties which had caused the first lines of this kind to be abandoned.

The outcome of their labours is given in two patent specifications dated 1845, and in a third in the following year, each of which described methods of enclosing the fibrous material in a casing of lead. The first, that of Wheatstone and Cooke, proposed that sheet lead should be folded round the cotton covering, and a longitudinal soldered joint made; or, as an alternative, that the lead should be moulded round the covered wire by hydraulic pressure, in the well-known manner of making lead tubes from semi-molten metal, The second, that of Young and McNair, proposed that the conductor, covered with cotton, should be drawn through a vessel containing the hot compound with which it was to be impregnated; and from this vessel through a tube, which passed into a cylinder containing lead at a temperature between 250° and 400° Fahr., and which terminated in a nozzle abutting against the die, through which the lead was forced out around the wire by hydraulic pressure. The third, that of Mapple, described a process in which the fibrous-covered conductor was drawn into a manufactured lead tube, which was afterwards drawn down by passing through rollers or dies, until it fitted tightly around the covered wire. The methods proposed by these inventors resemble very closely those which are in use at the present time; and the fact that this type of cable did not come into general use is no doubt due to the introduction soon afterwards of gutta-percha-covered wires, which at once took the first place in the estimation of telegraph engineers, who found them, though far from perfect at that time, much superior to the fibrous cables.

Since the re-introduction of this type of cable, many

improvements have been made in the details of the manufacture, and much more attention paid to the drying of the fibrous material, and to its thorough impregnation with compound; and it is now employed very largely in England, and on the Continent and in America. The materials used by the different manufacturers are cotton, flax, jute, or paper, impregnated with paraffin, ozokerite, bituminous, or resinous compounds; the lead casing is put on in a press either at a high temperature with a moderate pressure, or at a low temperature with an increased pressure; or the covered conductor is passed into a lead tube, which is afterwards drawn down by dies till it fits tightly, or is filled by injecting insulating material into it until all spaces, not occupied by the covered conductor, are filled up. Since the object of using the lead casing is to enclose the fibrous material in a waterproof covering, it is of the utmost importance that the method employed should be one that will ensure, as much as possible, the absence of flaws in the lead, and that will allow of the condition of the casing being ascertained during manufacture; and, for this reason, the method adopted for enclosing the covered conductor is a more important distinguishing feature of any system than the particular kind of fibrous material or compound which is used.

The Berthoud Borel cable may be taken as an example of the high temperature process, the covered conductor being immersed in a bath of hot linseed oil and resin, from which it passes, when thoroughly impregnated, direct to the lead covering press; where the lead in a molten condition is forced out through a die, through the centre of which the core is passed. This lead-covered core is then wrapped with compounded tapes, and a second lead covering is put on

as an additional protection; the object being the same as that with which such materials as rubber or gutta percha are put on in several distinct coats, namely, that any flaw in one covering may be protected by the other, which is not likely to be faulty also in exactly the same spot. From this point of view the second lead covering is a decided advantage, but it greatly increases the weight and bulk of the cable, and decreases its flexibility; and the fact that the makers have found it necessary to duplicate the lead covering, and thereby incur these disadvantages, appears to confirm the opinion that the lead is more porous, and less even in thickness, when put on at a high temperature, than it is when a greater pressure is used, and the temperature is lower.

The Siemens, Felten and Guilleaume, Fowler Waring, Callender, and Silvertown lead-covered cables are all examples of the low temperature process; and it is claimed for these cables that the lead covering, which is put on under very considerable pressure, and at a temperature which is well below its melting point, is stronger, less porous, and more uniform in thickness, than when a higher temperature is maintained. In the Siemens cable the conductor is wrapped with jute and impregnated with a special bituminous compound mixed with a heavy oil, and is then covered with lead. Over the lead is laid a covering of strong compounded tapes or jute, and on that two spiral wrappings of steel strip, and the whole cable is then served with compounded jute. The other cables mentioned above are made in much the same way, either armoured or unarmoured according to requirements, the compound used being generally a bituminous or resinous mixture.

In another lead-covered cable of this class, which

was first introduced by the Norwich Insulated Wire Company of New York, and is now made in England by the British Insulated Wire Company, paper is used instead of cotton or jute, as the material to be impregnated. The paper is wound on in strips spirally over the conductor, and as each spiral is laid on, it is passed through a die which presses it into a compact mass. The core is then exposed to a temperature of about 250° Fahr. to expel the moisture from the paper, and is immersed in a bath of special compound from which it passes direct to the lead-covering press.

With either of the methods of lead covering by a press, it is difficult to test the soundness of the lead, unless the cable is immersed for a very long time in water; and a partial flaw may easily exist, which, even after long immersion, will not allow moisture to get into the fibrous covering, but will, perhaps, develop into a complete fault after the cable has been coiled or uncoiled on drums, or in any other way been subjected to bending strains.

For this reason some makers have preferred to use the manufactured lead tube, which can be tested under pressure to see that it is sound, and to draw into it the covered conductor. The plan of drawing down the tube with dies is seldom used, as it leaves the fibrous covering exposed during the process, and it is consequently impossible to obtain a good insulation resistance owing to the absorption of moisture; but this difficulty may be avoided by filling up the space between the covered conductor and the tube with insulating material, instead of reducing the diameter of the tube itself. A good example of this class is the Patterson cable, in which the conductor is wrapped with cotton and impregnated with paraffin; it is then drawn into a lead tube, through which aerated paraffin is pumped under pressure. The act of filling is therefore a test

of the soundness of the tube and joints, as the pressure is sufficient to force the paraffin out through any weak places. The admixture of dry gas with the paraffin is made to render it more elastic, and also to reduce the electrostatic capacity of the cables; and it is claimed by the makers that the natural shrinkage of the paraffin, which is a great objection to its use, is compensated for by the expansion of the gas, and that the formation of cracks, through which moisture might penetrate in case of damage to the lead pipe, is prevented, and any fault caused by such an accident is therefore kept from spreading along the cable.

The readiness with which all fibrous materials absorb moisture makes it necessary to take special precautions for insulating terminal connections, and renders the liability to a decrease of insulation, wherever a joint is made, greater than with cables covered with a waterproof material. To overcome this difficulty, special cable terminals and joint boxes have been devised by the manufacturers of lead-covered cables, the former being used when connection is made to switchboards or other apparatus, and the latter when it is not convenient to make a lead-covered joint in the cable. If these special apparatus are not used, a joint is insulated by wrapping it with prepared tapes, great care being necessary to keep the exposed insulating material free from moisture; and over this wrapping a sleeve of lead is placed, which is fixed to the lead covering on either side by wiped solder joints. Sometimes the lead sleeve has a hole made in it near its centre, through which insulating compound is forced to fill up any spaces, and make the joint solid, the hole being soldered up afterwards so as to make all tight. When the conductor has to be bared to make connection to any apparatus in the circuit, the lead is cut back a

little way, and the exposed fibrous material dried by the application of heat: it is then tightly wrapped with rubber strip which extends a little way over the bare conductor at one end, and over the lead tube at the other end, so as to exclude moisture as much as possible from the insulating material.

The terminal and joint boxes used by different manufacturers are all much the same in principle, the idea in all of them being to enclose the exposed in-

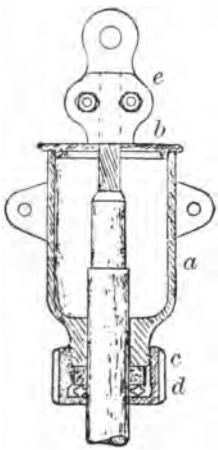

FIG. 35.

sulating fibre in a watertight box, filled with a heavy oil or other insulating compound.

The following illustrations of the apparatus used by Messrs. Felten and Guilleaume in connection with their lead-covered cables, will show very clearly the general plan which is adopted for this purpose. The box for terminating an ordinary single cable is shown in Fig. 35, in which *a* is a metal case, closed at the top with an ebonite cover *b*, and terminating at its lower end in

a gland with a rubber washer *c* and nut *d*. The method of preparing the cable is to cut off the insulation for several inches, and the lead tube for 2 or 3 inches more, leaving the fibrous material exposed. The end of the conductor is cleaned and tinned, and the fibrous covering trimmed down to a short taper; the nut, washer and case are then passed over the end of the cable and fixed in position on it, a tight

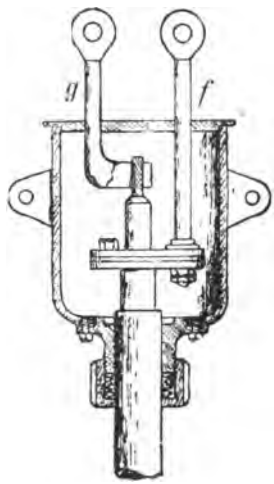

FIG. 36.

joint being made by screwing up the nut. The case is filled up with insulating material, which must be continually added so long as there are any signs of its sinking in level, and is then closed with the ebonite cover; and finally the projecting end of the conductor is screwed up tightly in the clamp *e*.

A similar box is used for terminating a concentric cable, the end of which is prepared by cutting off the lead tube for several inches, then cutting away the

outer insulating fibre to within an inch or two of the lead tube, and bending out the wires of the outer conductor at right angles to the cable, thus exposing the inner fibrous covering (see Fig. 36). This inner covering is then partially removed, so as to leave bare the end of the inner conductor as shown. The wires of the outer

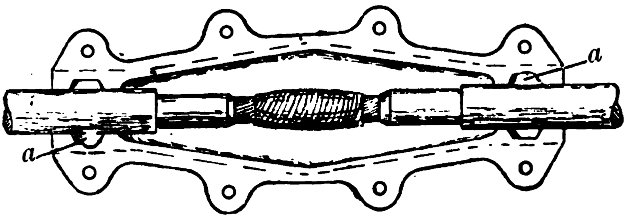

FIG. 37.

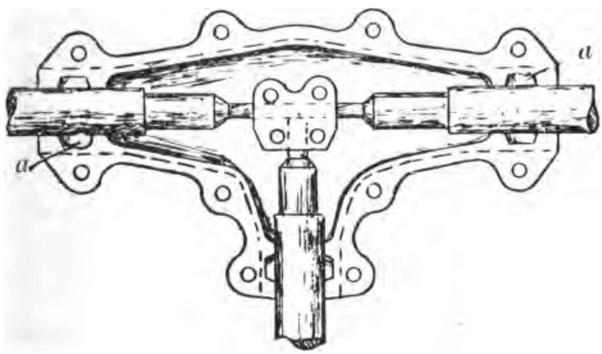

FIG. 38.

conductor are clamped between two metal plates *e*, to which is connected a gun-metal rod *f*; and the inner conductor is soldered or clamped to a bent rod *g*. The case is filled up as before with insulating material, and closed with an ebonite cover in two pieces.

For making straight or T-joints in the cable a clamp may be used, or the copper joints may be soldered in

the usual way; the joint in either case being enclosed in a box made in two halves, which are bolted together. Fig. 37 shows a soldered straight joint, and Fig. 38 a T-joint made with clamps. The ends of the cable are prepared in the manner already described, and the conductors soldered or clamped together; the lead tube being cut off, so that about 1¼ inches or more of it will project inside the box. The bottom part of the box is then placed under the joint, and the upper part over it; the two halves being bolted together with india-rubber packing between them to make a tight joint. In the top half of the box holes are provided, one leading into the interior proper of the box, and one into each of the small chambers marked *a*. Through these holes the main box is filled with insulating material, and the small chambers with asphalte; the holes themselves being afterward closed with screw plugs. Fig. 39 is an elevation of a similar box arranged for making a straight joint in a concentric cable, and Fig. 40 a plan of a box containing a T-joint in a similar cable. The inner conductors are connected by a clamp similar to that used for the ordinary single cable; and the wires of the outer conductors are, as before, bent out at right angles, and clamped between two plates, these plates being connected by coupling bars as shown.

The insulated conductors, which have been described so far, are all of them made in the factory in the form of cables of considerable length, and must therefore, for convenience of handling, be more or less flexible; but there is another type of insulated conductor which is supplied in short rigid pieces, which are jointed together during the process of laying; the most prominent examples of this type being the Edison and Ferranti tubes. The method of construction adopted with these conductors permits of the use of solid rods.

or tubes of copper of considerable sectional area, in the place of wire strands; but it also entails the making of a joint in the conductor once every 20 feet or so,

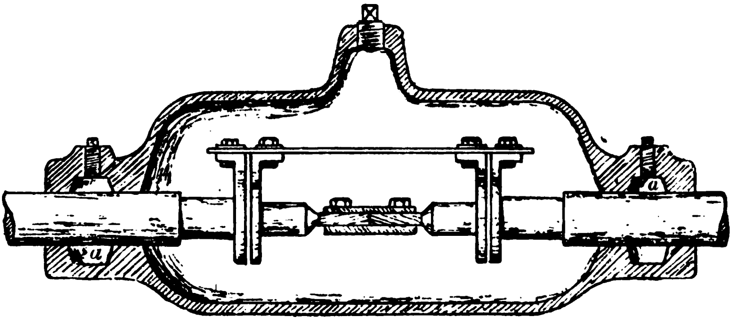

FIG. 39.

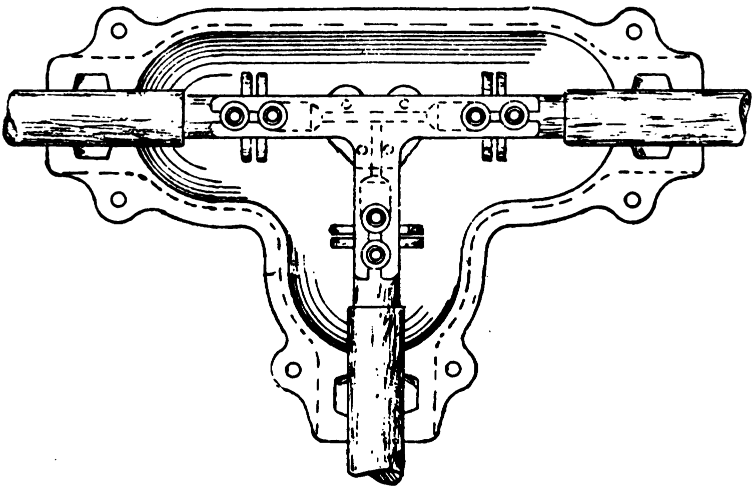

FIG. 40.

and therefore also a break in the continuity of the insulating covering.

The Edison system of underground mains was first

introduced about 1881, and was the first and, for a long time, the only system which could be fairly described as a complete one for dealing with the distribution of low-pressure currents by underground conductors. The details of construction of the tube have been modified in many respects from time to time; but, as at present made, the conductors, of which there are three, consist of solid copper rods about 20 feet long, which are spun over separately with dry string, and then placed in position in the centre of a steel tube. The length of this tube is somewhat less than

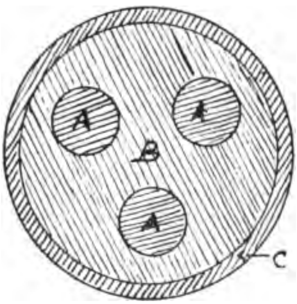

FIG. 41.
AAA.—COPPER RODS.
B.—INSULATING COMPOUND.
C.—STEEL TUBE.

that of the copper rods, so that the latter project a few inches at each end. This tube is connected to a pump, by means of which a vacuum is first created, and then a hot bituminous compound drawn in to fill up all the space within the tube, which is not already occupied by the conductors. By this means a three-wire main, (shown in section in Fig. 41), with the conductors surrounded with insulating material, and protected mechanically by the containing tube, is turned out in sections of 20 feet or thereabouts; and in this form the

sections are delivered from the factory to be laid in the ground, the joining together of the lengths being performed when they are placed in position. The connections between the corresponding copper rods are made by means of short lengths of flexible copper cable, to each end of which are sweated lugs provided with holes for the copper rods to enter (Fig. 42). A

FIG. 42.

split cap (Fig. 43), which forms part of a ball and socket joint, is then bolted to the end of each tube, and these caps are fitted into sockets prepared in the

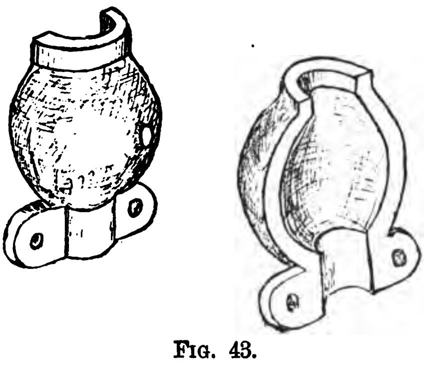

FIG. 43.

outlets of a split cast-iron box, the two halves of which are bolted together, so as to hold the caps, and therefore the tubes, firmly. The ball and socket joints allow of a limited deviation from a straight line in the alignment of the tubes, and give sufficient flexibility for the requirements of laying them in position under the

roads. The upper half of the cast-iron box is provided with a couple of holes, which can be closed by screw plugs, and which are used for filling in the box with a hot bituminous compound. For straight joints a box with an opening at each end is used (Fig. 44), and for T-joints one with three openings, as shown in Fig. 45, which also shows the method of connecting the main and branch cables.

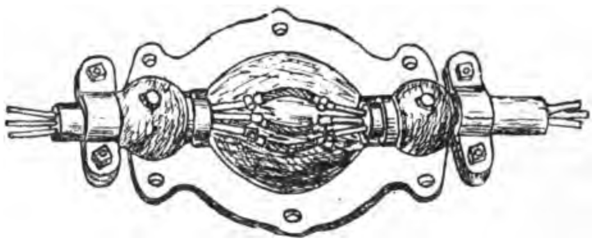

FIG. 44.

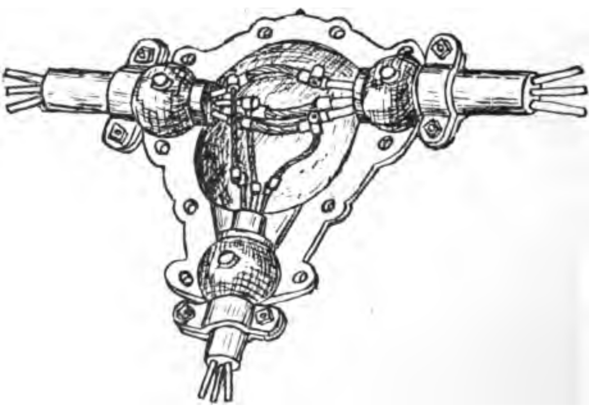

FIG. 45.

The Edison system has had a very extended use in America, where a large mileage has been placed under-

ground, and on the whole has given satisfactory results; although it has been by no means free from trouble as regards insulation. For distributing mains, the joint box every 20 feet is convenient, as it affords great facilities for branching off service wires; but the number of these boxes, and the difficulty of keeping them all watertight, is not conducive to high insulation resistance. The localizing and removal of a fault also necessitates the digging up of the conductor, and this opening up of the ground may become a serious item of expenditure, unless faults are of very rare occurrence. This system is used by most of the local Edison Companies in America, though this is not universal, as several of them are now using cables, as also is the Continental Edison Company in some of its installations in Paris and elsewhere.

The Ferranti mains, laid to connect the London Electric Company's station at Deptford with the distributing stations in London, are also made in short rigid lengths, delivered from the factory with their ends prepared for jointing; the joints themselves being made as the main is laid in the ground. This main, which is concentric, consists of two tubes of copper, one entirely within the other: the inner and outer tubes are insulated from one another by brown paper steeped in black wax, the outer tube is covered with the same insulating material, and the whole protected from mechanical injury by being enclosed in an iron tube (Fig. 46). The inner tube of copper is about 20 feet long, $\frac{9}{16}$ths of an inch internal diameter, and $\frac{13}{16}$ths of an inch external diameter, and on it are wound layers of the prepared brown paper, of a width equal to the length of the tube, until the diameter is increased to $\frac{27}{32}$nds of an inch. The insulated tube is then placed inside another copper tube, whose diameter is a little larger than that of the paper

insulation; and the outer tube is drawn down through a drawplate until it fits tightly over the insulation. The external diameter of the outer tube is $1\frac{1}{1}\frac{5}{6}$ths of an inch; and on it is wound brown paper, steeped as before in a bath of hot wax, to a thickness of $\frac{1}{8}$th of an inch, and the whole is then placed inside an iron tube about $\frac{1}{16}$th of an inch thick. This tube is provided with a hole through which hot wax is forced by a pump, so as to drive out the air, and make a solid mass of

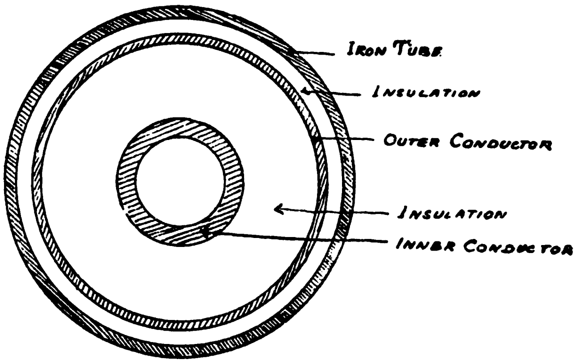

FIG. 46.

insulating material between the outer copper tube and the iron tube.

Each length of the main is then taken to a hollow spindle lathe to have its ends prepared for jointing, which is done in the following manner:—At one end a length of 17 inches is cut off the iron tube; the outer insulation, which is left exposed, is removed for a distance of 14 inches from the end; a length of 6 inches is cut off the outer copper tube; the inner insulation is turned so as to form a male cone, extending from the end of the outer copper tube to the end of the inner one; and finally the inside of the inner tube is


FIG. 47

rymered out for a length of 9 inches, so as to provide a truly cylindrical hole of the exact size required. At the other end a length of 11 inches is cut off the iron tube, and 8 inches off the outer insulation; the insulation between the two conductors is then turned, so as to form a female cone 6 inches long, which exactly corresponds with the male cone at the other end; and the inside of the inner tube is rymered out. A solid copper rod 18 inches long is driven into the inner tube for a distance equal to half its length, and a sleeve of copper 16 inches long is pushed over the outer copper tube, so that it encloses the 8 inches from which the outer insulation has been removed. This sleeve is firmly fixed in place by means of a tool, with which three or more circular corrugations are made, so as to indent both the sleeve and the outer copper tube. The tubes are now ready for laying, the joint (Fig. 47) being completed on the spot, by fitting the female end of one tube, with its projecting copper rod and sleeve, to the male end of another tube. The two tubes are drawn tight together by a screw press, whilst heat is applied to the joint to make the two coned surfaces of the insulation adhere to another; and the copper sleeve is fixed to the outer tube of the second length by means of circular corrugations made as already described. Before bringing the two ends together, an iron sleeve about 30 inches long is slipped on to one length; this sleeve at each end

nearly fits the protective tube, but is elsewhere somewhat larger in diameter; and in the enlarged part there is placed a sleeve of prepared paper. When the copper joint is completed, it is wrapped with insulation until the diameter is equal to that of the protected tube; the iron sleeve is pushed along so that it encloses the joint; hot wax is forced in through a hole in the sleeve to drive out the air, and fill up all spaces not already occupied by insulating material; the ends of the sleeve are fixed by circular corrugations, and the hole, through which the wax was introduced, is closed by a screw plug. Considerable difficulty was experienced at first in the making of these joints, owing to the system being an entirely new departure; but, when the men had been trained for a time and had got used to the work, the results were more satisfactory and the joints were made much better and more quickly.

Although the copper joints depend entirely on the surface contact due to the rod and sleeve making a tight fit with their respective tubes, the actual measured resistance of a main (which is 2·1 ohms for about 11,000 yards of double conductor), agrees very closely with the resistance as calculated from the sectional areas of the conductors; and this result is no doubt due to the large surface in contact at the joints, and the increased sectional area given by the rods and sleeves at these junctions. Dr. Fleming, in a paper on "Some effects of alternating current flow in circuits having capacity and self-induction," read before the Institution of Electrical Engineers, gave the following figures as the results of measurements made by him on a section of the main about 2,400 yards in length, the temperature being 32° Fahr.:—

Copper resistance, ·324 legal ohm per mile of double conductor.

Insulation resistance, 720 megohms per mile between inner and outer conductor.

Electrostatic capacity, ·367 microfarad per mile between inner and outer conductor.

From these figures it will be seen that the specific resistance of the insulating material is not very high, the ratio of outer to inner diameter of the insulation being about 2·3; but this is of little moment compared with its power of resisting disruptive discharge; as the resistance, which works out to 115 megohms for 11,000 yards, even if reduced by 50 per cent. by the temperature correction, is sufficient, if only it can be maintained constant under all conditions. The mains when laid were tested under a pressure of 20,000 volts, and with the exception of certain faulty joints, withstood the pressure; and since early in February, 1891, they have been in use with a working pressure of 10,000 volts. As regards insulation and the resistance to disruptive discharge, the weak point of the main is the enormous number of joints, at each of which the paper is divided, and the continuity of the covering depends on the wax only; so that there is a serious risk that, through bending, unequal expansion or contraction, or continued vibration, these joints will become faulty, and break down under the continued strain of the high pressure. This has actually been the case, and the trouble caused by faults at the joints has been so serious that the greater part of these mains has been taken up, and continuously insulated cable has been laid down to replace it.

Another method of effecting the continuous insulation of a conductor, is that known as the Brooks oil insulation system; and here again the complete insulated cable is not made in the factory, but part of the work of insulating the conductor is done when it

is in place. The conductor is braided with jute or hemp, which serves to keep it from mechanical contact with the pipe in which it is placed, or with any other conductor in the same pipe; and the insulation is effected by filling this pipe completely with a fluid insulating material. At first an ordinary mineral oil was used for this purpose, but owing to the difficulties arising from the leakage of this oil from the pipes, it has been replaced by a heavy oil of a resinous nature, which has the consistency of a very thick treacle, and has not therefore the same power of penetrating through the joints in the pipe. This oil is said to have a high insulation resistance, to resist disruptive discharge very effectively, and to be of a permanent character, as it does not become oxidized when exposed to the air.

The iron pipes, in which the jute-covered conductor and the oil are contained, are laid underground, and provided with drawing-in boxes, and junction boxes according to requirement; and, at the highest point in the line of pipe, a cast-iron tank with removable cover is fixed, which serves as an oil reservoir, and ensures the pipes being kept full of oil so long as it itself is kept charged. The inlets to the boxes through which the cables pass are generally provided with glands, by means of which a tight joint can be made; thus allowing the oil to be withdrawn from the box for testing purposes, or for connecting up a branch, without at the same time emptying the pipes. When the pipes and boxes have been laid and all joints in the same made tight, the cables are drawn in. To prepare them for this stage, the braided cables, which are brought from the factory on drums, are placed in a portable tank containing fluid insulating material, and are maintained therein, at a temperature

of about 300° Fahr., for a sufficient length of time to expel the moisture from the fibrous covering. They are then drawn into the iron pipes, into which the insulating fluid is forced so as to fill up all spaces not occupied by the braided conductors. To preserve the iron pipes from the action of the soil, they are often laid in wooden boxes which are filled up with hot pitch.

This system of insulation resembles in some respects those in which impregnated fibrous coverings are enclosed in lead pipes; but it is claimed for it that the iron pipe employed is less likely to be injured than a lead pipe, and that the insulating material, being in a fluid state, is free from the difficulties which are met with in the ordinary lead-covered cable, due to the compound not filling up any small cracks which may be caused by bending. On the other hand trouble may be caused by a leakage of oil, which is much increased when many branches are taken off the main cables, and this system therefore seems better adapted for use for feeders than for distributing mains.

CHAPTER XI.

Importance of Testing.—Mechanical Tests.—Electrical Tests.—Conductor Resistance.—Bridge Method.—Fall of Potential Method.—Localization of Faults.—Insulation Resistance.—Joint Testing.—Test for Resistance to Disruptive Strain.—Capacity.

A MATTER of the first importance, in connection with the manufacture of electric cables, is the tests to which they should be submitted; not only after completion, but also at different periods during the process of manufacture. These tests should be both mechanical and electrical, and should be made if possible under the actual conditions of the future working of the cable; but when, as is generally the case, it is impossible to exactly reproduce these conditions, the tests to which the cable is subjected should be rendered more severe, so as to allow of a fair margin of safety. The advantage of any test, which subjects the cable to a greater strain than that due to the normal working conditions, is that this increased strain is likely to break down any weak place which may exist; and which, although not bad enough to cause failure when the cable is new, may after continued use become a source of trouble. The particular test to which these remarks especially apply, is that of the insulation of the cable; and this test should always be made in water, and with a greater pressure than that which is to be used on the electric circuit, in which the cable will be connected. We have seen that the requirements, which have to be satisfied by an electric cable in order that it may be suitable for its work, are that the resistance of the conductor shall not exceed a definite

value depending on its length and sectional area, and on the conducting material employed; that the resistance of the insulating covering shall be high, and shall follow a determinate law depending on the same factors; that it shall be permanent, and not liable to be diminished excessively by exposure to fairly high temperatures, and that any such decrease of resistance shall be temporary, that is that it shall last only so long as the high temperature is maintained; that the resistance shall not be impaired by damp; that the insulating material used shall be capable of withstanding without injury the disruptive strains due to a high electric pressure; and that the capacity of the cable shall be as small as possible. Besides possessing these qualities the cable should have considerable tensile strength, and the insulating and protective coverings should be such as will enable it to stand without injury the handling, to which it will be subjected after it leaves the factory.

Some of these necessary qualities, which practically come under the heading of durability, cannot very well be tested except by continued use, but much valuable information might be gained by subjecting samples to continued changes of temperature, in moist and dry air; by immersing them in such liquids and gases as are known to be sometimes present in the soil or in the atmosphere; by subjecting them to tensile and bending strains, and to high electrical pressures; and by testing them for insulation resistance at stated intervals during the period of trial. By trials of this kind, in which the conditions may be made much more exacting than those which are likely to occur in practice, results might be obtained after the lapse of a comparatively short time, which would give a very fair guide to the relative merits of different methods of insulating conductors.

Tests for mechanical strength can be made on cables before delivery, such as the test for breaking strain, or the wrapping of the cable round a bar of small diameter; and tests of this nature, though seldom made, would often be useful in checking the manufacture; for instance, a rubber-covered cable which had been over-vulcanized, would not stand the wrapping test so well, as it would be more liable to crack; or a lead-encased and fibre-insulated cable which had been exposed to too high a temperature, or to too long continued a heat in the drying and impregnating process, would also fail owing to the weakening effect of extreme heat on the fibre. In both these cases the cable might be passed, if it were only subjected to the usual electrical tests, and it would leave the factory with the chance of being easily damaged by the first rough usage it received.

The electrical tests which have usually to be made in the factory are those of the resistance of the conductor, the localization of faults, the resistance and capacity of the insulating covering, and, when the cables are to be used with high pressures, the resistance to breaking down or disruptive discharge; and the methods of conducting these tests will therefore be briefly described.

All these tests should be taken with the cable immersed in water, in which it should be allowed to remain for twenty-four hours or more, before any measurements are made; and care must be taken to maintain the water at a constant fixed temperature, so as to ensure that the tests are made under such conditions as will allow of a proper comparison of the results with the calculated data of the cable.

The resistance of the conductor may be measured by the Wheatstone bridge, a metre bridge being probably

the most convenient form, as the resistances are generally small; or by the fall of potential method, in which a current from a battery of accumulators is passed through the conductor in series with a standard resistance, and the difference of potential between the terminals of the conductor is balanced against that of this standard resistance. The first method is the one most usually employed, the connections for it being made as shown in Fig. 48. In the ordinary bridge resistance box the resistances R_1 and R_2 may be ad-

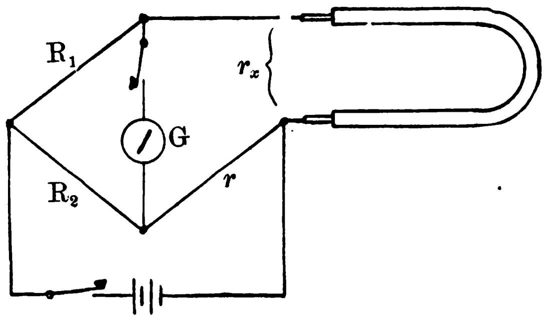

FIG. 48.

justed so that $\frac{R_1}{R_2}$ is any power of ten between 100 and ·01; whilst the resistance r can be adjusted by tenths of an ohm to any value between 9999·9 and ·1 ohm. The resistance r_x is given by the equation $r_x = r\frac{R_1}{R_2}$, and may be measured with fair accuracy if it is not less than one-tenth of an ohm.

For very low resistances the metre bridge is more convenient, that is, a bridge in which the resistances R_2 and r are replaced by a graduated wire, along which a slider connected to the galvanometer lead can be

moved, so as to make contact at any point along it. If, when equilibrium is obtained, the lengths of wire on either side of the galvanometer contact are respectively a and b units (see Fig. 49), then $r_x = R_1 \frac{b}{a}$. Great accuracy can be obtained by inserting resistance coils between the ends of the wire and the terminals to which the battery leads are attached; the effect being to virtually increase the length of the wire, so that each scale division becomes a smaller percentage of the total

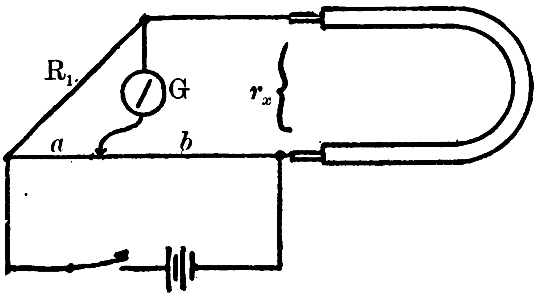

FIG. 49.

length. Of course the values of the added resistances must be known in terms of an equivalent length of the slide wire, and these values must be added to a and b in order that the equation given above may remain true.

With either of these arrangements of the bridge, two measurements have generally to be made, owing to the fact that the conductor under test cannot be connected direct to the bridge terminals; the first being the resistance of the conductor plus that of the wires connecting its ends to the bridge terminals, and the second the resistance of these wires or testing leads themselves. If, as is often the case, the distance from the cable tanks to the testing room is considerable, the

resistance of the testing leads may be greater than that of the conductor itself, and the possible degree of accuracy will then be much reduced. For example, suppose that the resistance of the conductor is x, and that of the testing leads y, the total resistance to be measured is $x+y$; then, if p is the percentage of accuracy that can be obtained, we can measure the resistance of $x+y$ correct within an amount equal to $\frac{p(x+y)}{100}$. This amount, however, is $p\frac{x+y}{x}$ per cent. of the resistance of the conductor; and therefore, if we suppose that we can measure a resistance accurately to one-tenth of one per cent., and that the resistance of the leads is five times that of the conductor, we cannot get this latter resistance nearer than six-tenths of one per cent.

For this reason, and also on account of the error introduced by the contact resistances when the leads are connected to the conductor or to one another, the second or fall of potential method is sometimes adopted for the measurement of very low resistances. To make this test, the conductor, whose resistance is to be measured, is connected in series with a standard resistance and a battery of accumulators, so that a current may be passed through the circuit. The standard resistance should be made of sufficient sectional area to carry the current without any appreciable rise in temperature; and it may be either a wire of fixed length and resistance, or a graduated wire like that used for the metre bridge, in which case one of the connecting wires is fitted with a sliding contact. One method of connecting up for this test is shown in Fig. 50, where R is the standard resistance, R_x the resistance to be measured, and r_1, r_2, r_3, and r_4 known resistances. When a balance is obtained, the following relation

between them holds good, viz. $\frac{R_x}{R} = \frac{r_3}{r_2} = \frac{r_4}{r_1}$. If a graduated wire is used for R, and the resistance r_1 connected to a slider, by means of which contact can be made at any point along R, then r_1, r_2, r_3, r_4 may all be fixed resistances, the value of R being adjusted till $\frac{R_x}{R}$ equals the ratio to which they have been set; but if R

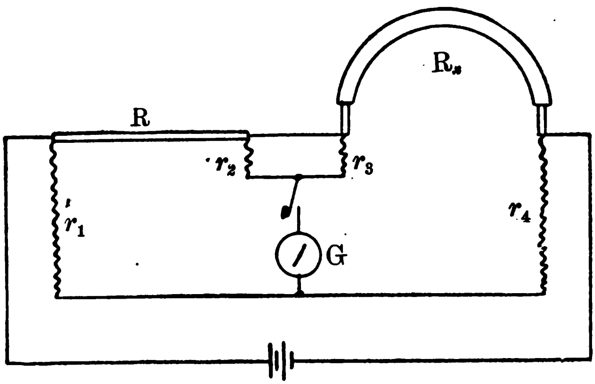

FIG. 50.

has a fixed value, then two of the other resistances, say r_3 and r_4, must be adjustable so that their values may be varied until $\frac{r_3}{r_2}$ and $\frac{r_4}{r_1}$ are each equal to $\frac{R_x}{R}$.

Another method is to use a differential galvanometer, the two coils of which are connected respectively to the ends of R and R_x (Fig. 51). If R is graduated, one galvanometer wire is moved along it until the galvanometer gives no deflection, which will be when $R_x = R$; or if R has a fixed value, then a resistance r in circuit with one of the galvanometer coils is adjusted, until a

balance is obtained, in which case $\frac{R_x}{R} = \frac{G + r}{G}$, if G is the resistance of each coil of the galvanometer.

Although under certain conditions greater accuracy may be obtained by the fall of potential method of measuring conductor resistances, the bridge method is the one most usually employed; since the apparatus for it is more conveniently arranged in connection with that which is required for other electrical tests. The

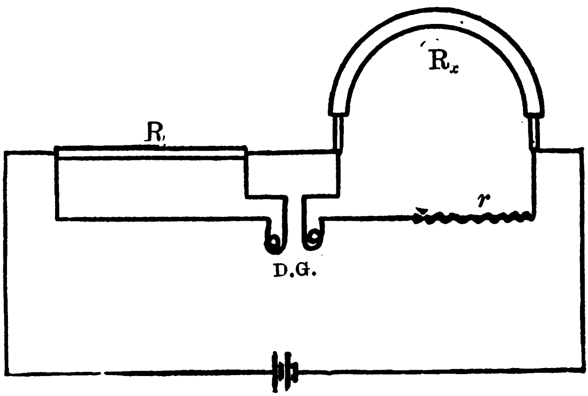

FIG. 51.

bridge may also be employed for localizing a fault in a length of cable by the loop test, the connections being made as shown in Fig. 52, where F is the fault. When a balance is obtained $\frac{BF}{AF} = \frac{R_2}{R_1}$, or $\frac{AF + BF}{AF} = \frac{R_1 + R_2}{R_1}$; but (AF + BF) and AF are proportional respectively to the total length of cable, and the distance of the fault from the end A, when the resistance per unit length of the conductor is the same throughout; and therefore the distance of the fault from A

$= \frac{R_1}{R_1 + R_2} \times$ length of cable. When the conductor resistance is not uniform throughout, as for instance when testing leads are used to connect the terminals A and B with the ends of the cable, the conductor resistance of each section must be obtained separately by the ordinary method, so that all resistances between A and B may be expressed in terms of the resistance per unit length of the conductor of the cable under test. If the resistance of the fault is high, a considerable battery

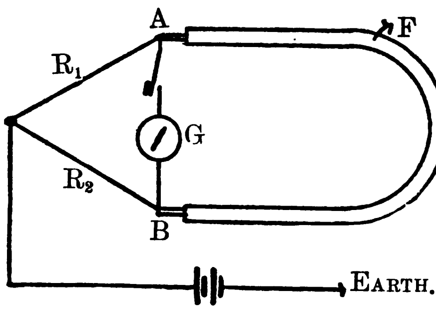

FIG. 52.

power is required to enable the test to be made with any degree of accuracy; and in the factory, where earth currents do not disturb the results, it is often more convenient to reverse the positions of the battery and galvanometer. This latter arrangement is very handy for use with the metre bridge, which may then be connected as in Fig. 53; since the distance of the fault from A may then be read off the graduated scale as a percentage of the total length of the conductor.

The insulation resistance of the cable may be measured by comparing the leakage current through the dielectric, with the current which will flow through

a known high resistance, when the same battery power is applied. The connections are shown in Fig. 54, where R is a known resistance, say one megohm; and K a key by means of which the galvanometer may be connected either to R, or to the cable to be tested.

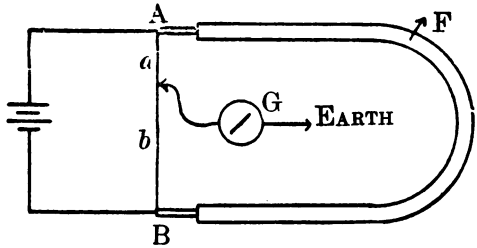

FIG. 53.

The constant is taken by closing the circuit through R, after having arranged a suitable shunt S_1, and noting the deflection θ_1 of the galvanometer. The key K is then changed over to the contact in connection with the cable, the galvanometer being short-circuited

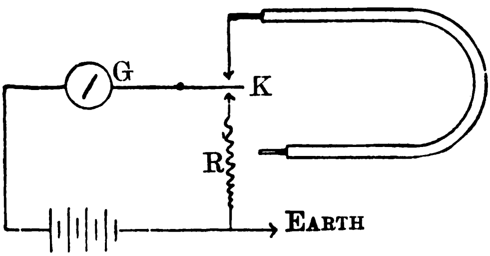

FIG. 54.

to prevent the first rush of current from passing through it. After a few seconds, the short circuit key may be opened, when the galvanometer needle will be deflected; but it will be found that the deflection is not a permanent one, but decreases gradually as the

current is kept on, owing to the electrification of the cable. One minute after closing the key K, the deflection θ_2 should be noted, as it is usual to specify the insulation resistance which is obtained after one minute's electrification. If a shunt S_2 has been used, the insulation resistance R_x is equal to $R \times \frac{\theta_1 \times (G + S_1) S_2}{\theta_2 \times (G + S_2) S_1}$, when G is the galvanometer resistance. The gradual decrease of the deflection due to electrification is often utilized as a further check on the soundness of the cable; as, if there is little or no electrification, or if it proceeds unsteadily, there is in all probability a fault in the cable. If the battery is taken off after electrification has been going on, say for fifteen minutes, and the cable is put to earth through the galvanometer, it will be found that a continually decreasing current will flow from the cable; and if this latter is sound, the deflections at the end of each minute will be found to correspond with those observed after equal intervals of time when the battery was on.

The measurement of insulation resistance should be made after the cable has been at least twenty-four hours in water which has been kept as nearly as possible at a uniform temperature; and the ends of the cable should be carefully prepared, so as to reduce the surface leakage to the smallest amount possible. This is most important, as, especially with short lengths of cable, it very often happens that, when this is neglected, the resistance proper of the cable is not measured at all; the deflection of the galvanometer being caused to a very great extent by the surface leakage at the ends. All tapes, braiding, or other covering, which may retain moisture, should be removed for a length of at least six inches; and the insulating material itself should be pared down with a clean sharp knife so as

to expose a new surface. The end should then be dried by allowing the flame of a spirit lamp to play round the core, care being of course taken that the insulating material is not burnt; and if the test cannot be taken immediately, the ends may be painted with hot paraffin wax. The end of the testing lead must be treated in the same way, and at the commencement of the tests, the deflection obtained when the end of the test lead is free should be noted, and should be allowed for in the subsequent readings.

It is always advisable to use as high a voltage as possible when measuring insulation resistances, so as to get a better chance of searching out any weak place in the dielectric; a convenient battery pressure being from 400 to 500 volts. This pressure may be too high to use when obtaining the constant through the standard resistance; and if this is the case, a portion only of the battery is connected, and the battery ratio is measured by comparing the discharges from a condenser, after it has been charged, first by the smaller and then by the larger battery. If the voltage of the whole battery is represented by B, and that of the part used for taking the constant by b, the ratio $\frac{B}{b}$ must appear in the formula, which will then become

$$R_x = R \times \frac{B\theta_1 (G + S_1) S_2}{b\theta_2 (G + S_2) S_1}.$$

When a joint has been made in a cable, it should always be tested, to see that its insulation is not very different from that of an equal length of the cable itself. Since the length of the joint is very small, it should offer a resistance far greater than can be measured by the direct deflection method described above; and special arrangements have therefore to be made for comparing the insulation of the joint with that of an

equal length of core. This may be done by what is called the accumulation method, or by using an electrometer. The joint in either case is immersed in water in a well-insulated trough, which may be of gutta percha or ebonite, and should be suspended by long ebonite rods. The connections for the accumulation method are shown in Fig. 55, where C is a condenser, and K a key that can connect one pole of the condenser either to the battery or to the galvanometer. The key K is closed on the lower contact, so that the

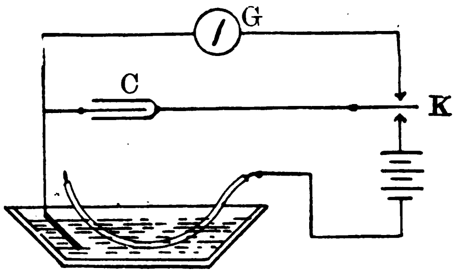

FIG. 55.

leakage through the joint charges the condenser, and is kept down for some stated time, say two minutes. At the end of these two minutes, K is switched over so as to discharge the condenser through the galvanometer, and the deflection thus obtained is compared with that given, when the joint is replaced by an equal length of perfect core. The insulation of the trough must be very good, and should always be tested beforehand. This may be done by connecting the battery so as to charge the condenser direct, and not through the joint; and then, having disconnected the battery, by allowing the condenser to stand charged for a couple of minutes before taking the discharge. If there is any appreciable leakage from the trough,

the discharge after two minutes will be less than the instantaneous discharge; and the insulation of the trough can only be considered satisfactory, when the two discharges are equal, or very nearly so.

The connections for the electrometer method are shown in Fig. 56, where E is the electrometer, and K_1, K_2, K_3, are keys for charging or discharging it. To test the insulation of the trough, close K_3 and K_1 on its upper contact, so that the small battery B_1 charges

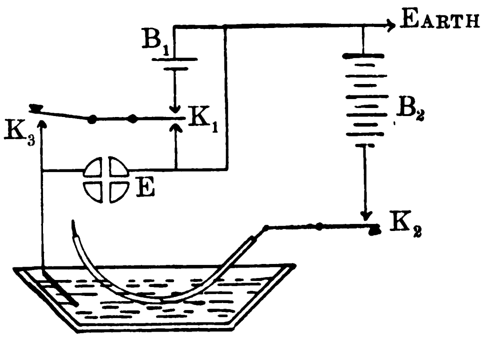

FIG. 56.

the quadrants of the electrometer, and gives a steady deflection; then open K_3, and note the decrease, if any, of the deflection, during say a couple of minutes. If this is very small, the trough may be considered to be well insulated. To test the joint, close K_2, thus charging the quadrants through the joint, and note the deflection after say two minutes, repeating the test again with an equal length of core instead of the joint; the two deflections should not differ very much if the joint is good.

The ordinary insulation test which has been described is sufficient for cables intended for low pressure work, where the strain on the cables is so

small that there is practically no chance of the current breaking through the dielectric, and where also the testing battery can be conveniently arranged to give a pressure several times as great as the working one; but for cables intended for high pressure work, a strain at least twice as great as that due to the working pressure should be applied, and this cannot be done conveniently with the testing battery. In such cases, therefore, a separate test should be made, in which the cable is subjected to a high pressure; and this is most conveniently done by the use of an alternating current transformer. The primary circuit of this transformer may be wound for any suitable voltage; and the secondary circuit should be divided into several separate coils, the ends of which are led to terminals, arranged so that the multiplying ratio of the two sets of windings may be varied to suit the requirements of different tests. The transformer may be wound to give a maximum pressure of 10,000 volts by steps of 1,000, or perhaps 2,000, volts per coil; and it must be capable of carrying a current of two or three amperes at least, if cables of considerable capacity are to be tested; as the condenser current may easily reach this amount, when a mile of cable is tested with 10,000 volts at a frequency say between 60 and 100 per second. For cables which are to be worked at 2,000 volts or thereabouts, a test pressure of 4,000 or 5,000 volts should be applied continuously for several hours, the cable of course being immersed in water; and after this, the insulation test should be repeated to see if there is any change in the resistance. This apparatus is also useful for breaking down a high resistance fault, and making it easier to localize by the loop test. This high pressure test should also be applied after any mechanical test, for example, a

length of several feet cut from the cable should be bent several times, first in one direction and then in the other round a cylinder, and the sample should then be subjected to the high-pressure test to see if it has been injured by bending.

The capacity of the cable may be measured by comparing the discharge from it, with that from a condenser of known capacity, the connections being made as shown in Fig. 57; where C is the condenser, and K_1 and K_2 are two discharge keys. Connect K_2 to the lower contact, and K_1 to the left-hand one, so as to charge the condenser. Switch K_1 over to the right-

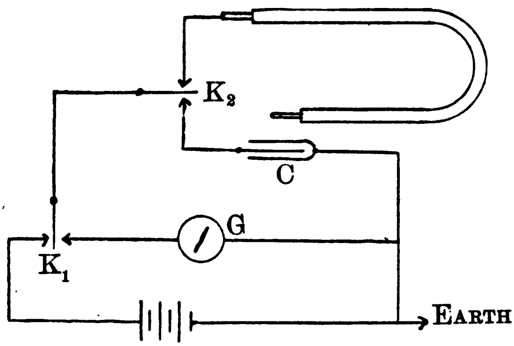

FIG. 57.

hand contact to discharge the condenser through the galvanometer, and note the discharge deflection, say θ_1 with a shunt of S_1 ohms. Having first earthed the conductor, to remove any residual charge, change K_2 over so as to connect it to the cable, and repeat the test, getting a discharge deflection, say θ_2 with a shunt S_2. Then if F_1 is the capacity of the condenser, and F_x that of the cable,

$$F_x = F_1 \times \frac{\theta_2 \times (G + S_2)S_1}{\theta_1 \times (G + S_1)S_2}$$

CHAPTER XII.

Internal Wiring.—Danger from Introduction of High Pressure in House Circuits.—Fire Risks.—Current Density.—Fusible Cut-outs.—Insulation.—Mechanical Protection.—Wood Casing.—Metal Tubes.—Paper Tubes.—Double and Single Wire Systems.—General Arrangement of Circuits.—Tree System.—Distributing System.—Testing of Circuits.

In the preceding chapters we have seen how to determine the most economical size of conductor, and what rules must be observed to prevent the rise of temperature due to the passage of the current from becoming too great for safe working, and to keep the variation of pressure at all parts of the circuit within certain permissible limits; and, further, the various methods of insulating conductors have been described, and their respective advantages and disadvantages have been pointed out. It is now necessary to consider how these rules can best be applied in special cases, and how the conductors should be fixed in position, and protected from mechanical injury. For this purpose it will be convenient to discuss separately the three following cases: viz., Internal wiring, aerial lines, and underground lines.

The working pressure on circuits fitted up in buildings or ships rarely exceeds 200 or 220 volts, and is often less; so that, unless by some accident a higher pressure is introduced from external supply mains, no dangers need be apprehended from personal contact with the conductors. To guard against any accidental introduction of a dangerous pressure, the external

supply mains, if directly connected to the house circuits, should not be worked at more than about 400 volts, as a leakage on one part of the circuit may expose any person touching a conductor to the full pressure; and, when transformers are used to reduce the pressure, they should be so arranged that a contact between the high and low-pressure circuits is only possible when contact is also made with the earth at the same point. For this purpose the two sets of coils on some alternating and continuous current transformers are arranged in such a manner that they are divided by a metal partition which is in contact with the earth; and, when this is the case, it is evident that any leakage from one coil must go to earth before it can get to the other coil, and that the difference of potential between either of the low-pressure conductors and the earth can never be increased above that which normally exists between the two conductors.

When these or other precautions which will be discussed in Chapter XV. are taken, all danger from personal contact with the conductors is removed; and the most important problem to be then considered is, what methods of arranging the conductors will best guard against any risk of fire, due to the presence of combustible material, which is always to be found in fairly close proximity to the wires in buildings or ships. That such risks do exist must be allowed by all; but although there are differences of opinion as to what is the best thing to do under given conditions, and objections may be raised to some of the methods which have been generally adopted; yet it may be safely said, that perfectly satisfactory results can be obtained by following any of these different plans, if only good material and workmanship are employed throughout, and the work is supervised during its progress by a

competent foreman, who can be trusted not to pass any scamped joints, and to test from day to day to see that the wires themselves are not damaged in fixing.

The overheating of the conductors may be guarded against by making them of ample size for the normal current, and by inserting in the circuit fusible cut-outs which will melt and break the circuit, if the current by any accident becomes excessive; and the local overheating, which may be caused by a break or partial break in the conductor, or by a bad joint, can be prevented by careful workmanship and supervision, and by using wires of sufficient section and flexibility, to enable them to withstand without injury the bending and other strains, to which they may be subjected when being fixed.

Various rules for limiting the current to be carried by any conductor are specified in the regulations which have been issued by the Institution of Electrical Engineers, the Insurance Companies, and the Supply Companies. Table II (pages 20 and 21) gives the current for each size of conductor which will raise its temperature 18° Fahr. above that of the surrounding atmosphere, the figures being calculated from the formula deduced by Mr. Kennelly from the experiments made by him in 1889. As explained in Chapter II., this formula was worked out to give the sizes of conductors required by the then existing rules of the Institution of Electrical Engineers. In the author's experience the current-carrying capacity of any wire or cable calculated from it is such as may safely be used without fear of undue heating, and the smaller current densities allowed by the 1897 rules of the Institution are by no means necessary.

It must, however, be noted that for the smaller wires the current density is not, as a rule, limited by

the rise of temperature, but by the maximum allowable fall of pressure; and for very small currents by considerations of the mechanical strength of the conductors, and that in such cases the current density in practice is always much less than that which would be allowed if heating were the only consideration.

As regards mechanical strength, the safe limit is certainly reached with a No. 18 wire, as there is too much risk of the conductor being broken if of smaller diameter; and this wire, which will therefore be used to carry the current for only one lamp, is, according to the table, actually capable of carrying a current of six amperes, or sufficient for say sixteen lamps of 8-candle power and 100 volts pressure. If it were worked at six amperes, the fall of pressure would be at the rate of one volt for every twelve yards of conductor, or six yards run of double lead, which is a much greater fall than could be allowed for satisfactory lighting. Although the drop of pressure is not so great with larger conductors worked at their utmost safe current, it is more than can generally be allowed; since, as the number of lamps, and therefore the current, is increased, the distance of the farthest lamp from the main terminal increases also; for example, supposing the fall of pressure is arranged at an equal rate throughout the circuit, a strand of 19 No. 16 could only be worked at its maximum safe current, when the most distant lamp was about 100 feet from the terminals; and this is by no means a big allowance, when we consider that there would in this case be 250 lamps of 8-candle power on the circuit, or half that number of 16-candle power lamps.

A rule, which is often specified, allows a current density at the rate of 1,000 amperes per square inch of conductor area; and although, as regards heating of

the wire, it is wrong in principle, and actually unsafe for very large sizes, it has the great advantage of being definite and easily understood, of being fairly economical, of being safe as regards heating for all conductors up to about a quarter of a square inch area, and of keeping the fall of pressure within reasonable limits on all circuits, where the lamps are not more than 150 feet or so from the terminals. With conductors of comparatively small sectional area, like those which are most frequently used for internal wiring, a current density of 1,000 amperes per square inch allows a considerable safety margin, and a current of double the normal strength can in most cases be carried by them without undue heating. This safety margin is most useful, since the possibility of the passage of a current much greater than the normal must be considered.

Damage from overheating is usually prevented by the use of fusible cut-outs, which are arranged to melt when the current increases by some fixed percentage; and the number of these cut-outs which must be fixed, and the increase of current that can be allowed by them, depends on the safe current-carrying capacity of the wires. If the wires are in all cases only just large enough for their respective currents, a cut-out must be placed at every point where a wire of smaller sectional area is branched off a larger one; and the fuse must be arranged to melt with a very small increase of current above the normal; whereas with conductors of larger area a smaller number of cut-outs will suffice, or they can be arranged so that they will not melt without a considerable increase of current. Now, cut-outs should always be placed in easily accessible positions, and it is often difficult to arrange for this when there is a large number of them; and further, they should never break the circuit with the usual working current

as many do after being in use for some time, because the natural result of such behaviour is, that the man who is looking after the lights, puts two fuse wires in instead of one, to save himself the trouble of frequent renewals, especially if he has to get a ladder or steps each time to reach up to the cut-out. A smaller number of cut-outs, fixed in easily accessible positions, with fuses so proportioned that they require about a hundred per cent. excess of current to melt them, will have a much better chance of protecting the circuits; and there is very little difficulty in arranging them on these lines so as to be perfectly safe. For example, when the smallest wire in use is a No. 18, which will carry six amperes, or say the current for sixteen 8-candle power lamps, a double pole cut-out fixed for each group of eight lamps will give ample protection; there will be but little danger of the lamps being extinguished, when the circuit is in good working order; the user of the lamps will not be inconvenienced so often by their going out; and, owing to the rarity of the occurrence, he will be far more likely to test his circuit to see if anything is wrong with it.

There is however one advantage gained by the use of a large number of cut-outs, viz., that the circuit can be divided up into a number of very small sections, which facilitates the localizing of a fault; but, if on this account cut-outs are fixed in every branch, there is still no reason why the fuses should not be all arranged to melt at the maximum current that the smallest wire will carry, so as to avoid the inconvenience of frequent renewals.

There is an old saying, that prevention is better than cure, and this holds good in the present case as in most others; so that, although the cut-out cannot be dispensed with altogether, the best way of guarding

against overheating of the conductors by the passage of an abnormal current, is to minimize the chances of leaks by the use of well-insulated wires. A well-insulated wire need not necessarily be one that gives an extremely high insulation resistance per unit length; but it must be one that gives a constant resistance under all conditions; and the material used must therefore be durable, waterproof, and capable of withstanding variations of temperature over a considerable range without permanent damage to its insulating properties, and without being rendered brittle enough to crack or soft enough to allow of the conductor sinking through it. The insulation of the conductor should be independent altogether of any help from insulating material which may be used for mechanical protection; in fact, no cable or wire should be employed that cannot stand the test of continued immersion in water; and any rule like that given by the Phœnix Fire Office (viz., that conductors should be so arranged that they will still be practically insulated in the event of their insulating coverings getting worn away or removed) is unsatisfactory; followed as it is by the recommendation of wood casing, which more often than not is a sufficiently good conductor to allow of a leakage current passing, which may char and possibly set it on fire. This plan of adding a partial insulation in series with that of the wire itself has many objections, unless the insulating casing is absolutely non-combustible; since it may render a leakage current too small to be easily detected, or to melt a fuse, and yet allow it to be large enough to cause a risk of fire; and this is exactly what is not wanted.

In the ideal installation the insulation resistance is normally high, but falls off very decidedly when a fault occurs, so that there is no difficulty in finding it;

and the insulated conductor is placed in such a manner that under no circumstances can a leakage current pass through any combustible material which is in proximity to it, and also so that, when a fault occurs, it may be remedied without cutting away the floor or walls of the building. These conditions may be fulfilled by fixing metal-encased wires on the surface, or by placing the wires in metal or other non-combustible tubes, into or out of which they can be drawn as occasion requires. Although these methods of construction have until recently been little used in buildings, they have been extensively employed on shipboard with very satisfactory results. Many ships are wired throughout with lead-covered cables, the dielectric being either rubber or impregnated fibrous material, these cables being fixed on the surface of the bulkheads by cleats in such a manner that they are always exposed to view and easily accessible; and in many other ships, although wood casing is used in the cabins, the wires in the engine-room, stoke-hole, cargo spaces, etc., are run in iron pipe, provided with split T-boxes at places where branch leads are jointed to the mains. This latter method is a very good one, as the iron pipe affords an excellent mechanical protection; and, owing to its large sectional area, cannot be raised in temperature to a dangerous extent by any leakage current which is not big enough to melt the fuses. If split boxes are fixed in proper positions, the system becomes a very convenient one for drawing in and out conductors, should it be necessary to make any repairs.

For the internal wiring of buildings in England, grooved wood casings have been generally employed; and, owing to the space occupied by them and to their unsightliness, they are very frequently let into the walls, where they are out of sight and inaccessible,

without cutting away the wall papers or other decoration. The wood casing also frequently acts as a sponge, and absorbs any moisture that may exist in the surrounding plaster; and further it does not sufficiently protect the wires mechanically, as, for instance, from being damaged by having nails driven into them. Although excellent work has been done where the wires are enclosed in wood casing, the good results are probably due more to the quality of the insulated wires and to the care in fixing them, than to any benefit derived from the use of the casing; and it is therefore somewhat surprising that such implicit reliance should be placed on it, as would appear to be the case from a study of the regulations published by Insurance and Supply Companies.

Owing to the objections mentioned above, the use of tubes has greatly increased, and several firms have made a speciality of the supply of tubes, and of joint, switch, and fuse boxes to be used with them. The use of iron pipe in ship work has been already mentioned, and the same system is now employed in buildings, the pipes being either cleated to the walls and ceilings, or, where this is objectionable on the score of unsightliness, as in private houses, embedded in the walls. Unions and bends are supplied to join the lengths of pipe together, and watertight boxes are fixed at convenient positions to allow of the wires being drawn in after the pipe work is finished, as also are other boxes containing switches and fuses. These boxes may be let into the walls so that only their covers project beyond the surface, or may be fixed on the walls, according to the position of the pipes. Great care must be taken that no burr is left inside the pipe when it has been cut, as otherwise the wires might be damaged in drawing them in; but if this precaution is taken, well insulated

wires employed, and all joints in the wires made in joint boxes so that they are easily accessible, this system offers many advantages and makes an excellent installation.

Another system of tube wiring is that introduced by the Interior Conduit Company in America, and now largely used in England and on the Continent, which provides pipes with drawing-in and joint boxes in a somewhat similar fashion to the iron pipe system already referred to. These pipes are made of paper soaked in a bituminous compound; and it is claimed for them that they are strong, tough, and waterproof, that they can be made fireproof by coating them with a suitable paint, that they are very easily fixed, and that they allow of the wires being drawn in or out as required. There is a further claim, that the bituminized paper tube is such a good insulator, that it is unnecessary to use more than a light covering of fibrous material on the wires; but, as the two wires are run in the same tube, there would be, at any rate in our damp climate, a plentiful number of short circuits, which, although they might afford an opportunity of demonstrating the convenience of a drawing-in and out system, would hardly conduce to satisfactory working. With properly insulated wires, however, such a system has many advantages; and now that further improvements have been introduced, and that the tubes are supplied brass or iron armoured, that is to say, that a brass or iron tube is supplied with a paper tube fitted into it, this system affords as good a mechanical protection as the plain iron pipe with the advantages, or, in the opinion of some engineers the disadvantages, of an added insulating lining. The presence of the paper tube does away with the risk of a burr being left inside the iron pipe

by a careless workman, and it is claimed that it is more difficult to damage the tube by burning a hole in it should a short circuit or fault occur on the wires. On the other hand the armoured paper tube is necessarily more expensive than the plain iron tube, and the fact that the insulating lining is not continuous, and will allow a surface leakage to the outer tube at the joints gives rise to the same objectionable feature of adding a partial insulation in series with that of the wire; viz., that the wire may be damaged and a fault exist whose resistance is too high to permit of its being easily localized.

The wiring of all buildings to which current is supplied direct from central stations must generally be carried out with two insulated wires, one for the out and one for the return; but in isolated plants, and when the internal wiring is in no way connected with the supply mains, or one of the supply mains is earthed, the single wire system may be used, in which the earth or an uninsulated wire is used for the return. This system has as yet been seldom employed except for ship-lighting, in which the metal skin of the ship itself is used as the return wire; but a system, in which the return wire takes the form of a sheathing of iron wires concentric with the insulated conductor, has been developed by Mr. Andrews, and has been brought to the notice of the Fire Insurance Offices with a view to its introduction in land installations. Both the double wire and single wire systems, when carefully erected, will give satisfactory results, and the claims which have been made for each by their respective advocates are a good deal exaggerated, as we shall see in Chapter XV. when discussing the advisability of earthing one pole of the supply mains.

The single wire system was first used for ship-light-

ing because only half the amount of wire was required, and it was thought therefore to be much cheaper. That it may be cheaper there is no doubt; but, if equal insulation is provided, and the concentric form of conductor is used, the difference will be very much less than is often supposed; and even if ordinary wires are used in wood casing, the cost of running return wires from the lamps to the hull of the ship, and connecting them thereto, must be taken into account. These connections have sometimes been a source of trouble, through corrosion at the point of contact between the wire and the framework of the ship, with the result that an extra resistance is introduced; and as the connections are not generally in accessible positions, it is difficult to get at them and overhaul them.

With regard to the effect of the current on the ship's compasses, it is now generally acknowledged that all wiring, within, say, 20 or 30 feet of a compass, should be carried out with an insulated return, so as to avoid the errors produced by the unbalanced effect of a current in one direction; but Lord Kelvin, in a paper read before the Institution of Electrical Engineers in 1889, pointed out that even with this precaution an error would still exist, owing to the hull of the ship being connected as a shunt on the insulated return wire, so that the currents in the out-going and the return conductors would be unequal. The same error may exist in a ship with double wiring, if two points on the same side of the circuit make connection with earth, one leak being between the dynamo and the compass, and the other beyond the compass; but in this case the fault can be remedied by repairing the insulation of the wire, whereas with single wiring the use of the hull as a return is an integral part of the system.

With either of these systems the general arrangement of the conductors may be carried out in two different ways. In one (fig. 58), which may be called the tree system, branches are taken off the main conductors, and from these branches others are taken, the branching off being continued until finally the lamp wire is reached; and in the other (fig. 59), which may

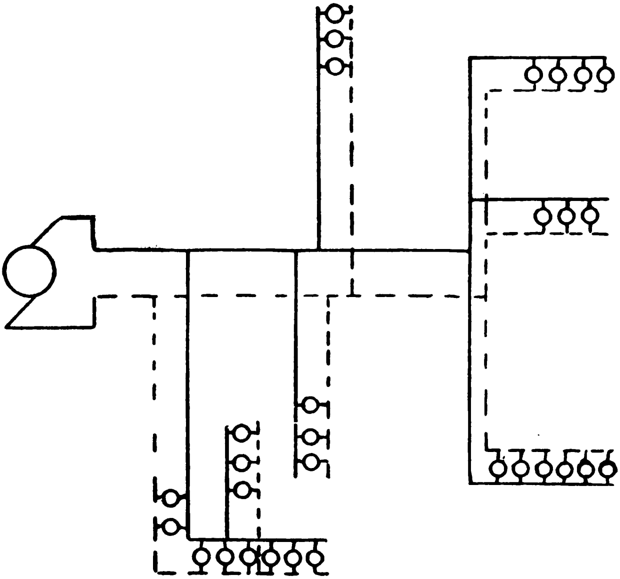

FIG. 58.

be called the distributing system, a large number of small circuits start from one or more distributing boards, each of which may be connected by its own pair of cables to the main switchboard.

The second, or distributing, system has recently come into great favour, and is now very extensively employed; since, although it is not so economical in wire,

it reduces the number of insulated joints in the circuit to those required for the actual lamp branches ; and these joints are always the weakest part of the insulated wire, and have frequently to be placed so that they are difficult of access. In some cases the wiring is arranged so that there are no insulated joints in the circuits at

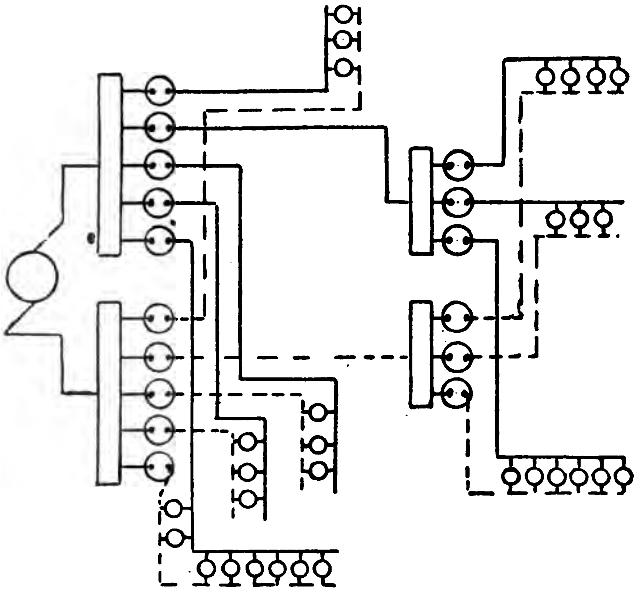

FIG. 59.

all ; for example, in an ordinary house a distributing board may be fixed near the dynamo or other source of current, and from this a separate circuit may be run to a distributing board on each floor; from these, circuits may be run to a board in each room, from which separate wires are run to each lamp; or a separate circuit may be run to each room from the main distributing board, thus doing away with the board on

each floor. This method of wiring, besides doing away with all joints, allows all the cut-outs to be grouped together on the distributing boards, where they are easily accessible; and, if more convenient, the switches also may be fixed on these boards, or may be grouped together near the doors of the various rooms.

This arrangement of circuits, combined with a system of pipes into or out of which the wires may be drawn, and with cut-outs fixed on distributing boards, so that they each control a circuit of 8 or 10 lamps, will give the most satisfactory results, since the insulation of the wires is left intact throughout their whole length, which decreases the chance of leakage from them; repairs, if necessary, can be made without interfering with the decorations of the walls; and the cut-outs are visible and accessible, and may be more easily arranged so that they themselves cannot, by failing to work properly, be the cause of a fire. Of course the smallest wire on any circuit must be large enough to carry the fusing current of the cut-out without injury; and this, together with the use of a much greater length of comparatively small wire instead of a short length of larger wire, will increase the cost of the wires and casings; but the saving of labour in jointing, and the smaller cost of the cut-outs will, to a great extent, if not entirely, counterbalance any increase of cost on this account.

Whatever arrangement of circuits and methods of fixing the wires are adopted, the final result must depend on the quality of the material and workmanship; and, to ensure that this is good, there must be constant supervision by a competent foreman, and frequent tests of the circuits whilst the work is in progress; so that faults, either in the conductivity or insulation of the wires, may be at once located and removed. Several very useful and compact portable testing sets are on

the market, with which the conductivity and insulation resistances of the wires may be measured; and if these tests are systematically taken day by day, no faults need be allowed to pass unnoticed. Too frequently the testing of the circuits stops when the Insurance Office or Supply Company have passed the installation, and most users of the light consider that this must be so, since they themselves are not electricians; but for isolated installations there are several very simple methods of detecting the existence of a leakage whilst the current is on; and it would be to the interest of all parties if suitable apparatus were fitted up as part of the installation, and the user of the circuit would test it every day. Several of these methods are described in Chapter XVII., the lamp method being the simplest and least expensive, when switches are provided so that the lamps are out of circuit except at the times when a test is being made.

These tests cannot, however, be employed for installations connected to public supply mains on any system except that in which there is a transformer for each installation; as where a number of installations are connected to the same mains, a test made at any one of them will measure the resultant leakage of all. In this latter case, a special form of voltmeter test may be employed, as described in Chapter XVII., which, if all the lamp switches are opened, will measure the actual leakage current from each pole of the installation to earth.

CHAPTER XIII.

Overhead Lines.—Objections to their Use.—Materials for Overhead Lines.—Wire and Cables.—Bearer Wires.—Poles.—Insulators.—Lightning Protectors.—Bare Wire Line.—Cable Line.—Cable Line with Bearer Wires.—Earthing the Bearer Wire.—Mechanical Strains on Wire and Poles.—Calculation of Strains.—Average Wind Pressure.

FOR outdoor work the conductor may either be placed overhead or underground, each method having certain advantages over the other; and a decision as to which is the better to use for any particular installation can only be arrived at after all the conditions of the case are known. There are, however, certain points which must be taken into account in any comparison between the two methods of placing the conductors, such as their relative costs both as regards capital expenditure and maintenance, and their relative safety to the public.

In the matter of first cost, the advantage is decidedly on the side of the overhead wire, except when very large conductors are employed; as the trenching, and pipes or other conduits, required for the underground main are much more costly than the poles and insulators which support the overhead wire; but, as a general rule, it may be taken that a well insulated cable safely laid underground will cost less for maintenance than if placed overhead, owing to the fact that it is not exposed to the same extent to the chance of mechanical injury from storms of snow and wind, or from lightning strokes; and that it is placed in such a position that variations in atmospheric conditions can

have little effect on it. Much will depend on the class of cable used, and on the degree of efficiency, as regards insulation, which is considered necessary; as, with an inferior class of cable, the underground main may be very expensive to maintain on account of continual failures of the dielectric, which must be repaired to enable working to be continued; whilst with the overhead wire the insulation of the cable is supplemented by that given by the supports, and this latter may have sufficient resistance to allow of the line being worked.

It is, however, when the safety of the public is considered that the expense of maintaining the overhead line is increased; as, if high pressures are used (and it is only in such cases that there is much to be gained in first cost), the cables must be quite as well insulated as those required underground; and the line must be periodically inspected, and poles, stays, bearer wires, etc., replaced, as they show signs of deterioration, so as to avoid all chance of injury through the breaking of any one of them. At intervals of a few years the Post Office and Telephone Companies have to make a wholesale renewal of much of the system of overhead lines, owing to their destruction by a violent gale of wind accompanying a snowstorm; and the possibility of such an occurrence must be taken into account, and the overhead line must either be made so strong mechanically that it can withstand such storms—and this means a considerable expenditure of capital—or one must be prepared for an occasional breakdown with the consequent loss of business and cost of renewal.

For these reasons it will be found more economical to place the wires underground, except in districts where the houses requiring the current are very scattered, or

a new district is being exploited; in which case, or when electricity is transmitted to a considerable distance for driving motors, etc., it may often happen that an underground line is not possible commercially; for example, if water power can be obtained at a distance of several miles from a mill or factory, and it is proposed to erect turbines and dynamos at the one place and motors at the other, it may happen that the interest on an underground line, added to that of the other plant, will come to as large a sum as the annual cost of power derived from another source; so that, unless an overhead wire can be used, the scheme becomes economically impracticable.

The objections to the use of overhead lines, briefly stated, are their liability to mechanical injury through wind storms, to electrical injury from lightning, and the possibility of accidents being caused by the breaking of the conductor, or by its contact with a human being or with other conductors. None of these objections present any very serious difficulty, and they may all be overcome by the use of good material, careful erection, and efficient inspection at frequent intervals after the line is working; but this all adds to the expense, and, unfortunately, much of the overhead work that has been done has been put up for cheapness, and therefore in the worst manner possible; with the result that accidents have happened, and a great outcry has been raised against all overhead wires, and their use has been condemned indiscriminately. In large towns it is advisable not to use aerial lines, because it is often difficult to keep down the length of the span at street crossings, so that there is a greater chance of accidents happening from a broken wire; and, when such accidents occur, they may be more serious in the towns than elsewhere; but these objections do not apply with

the same force in many smaller towns, or in the open country, and there is, therefore, no reason for preventing the erection of overhead wires in such cases, when economy results from their use. Two cases may be considered: one in which the line is carried on poles across country, and consists of bare wires; and the other in which the line is carried over the housetops, or along the side of the public roads, in which case the wire must be continuously insulated.

The bare wire line must be erected in such a way that the conductors cannot come into contact with one another, or with any neighbouring wire, tree, or other substance that might cause a short circuit between them; and also so that it is difficult of access to the public, who should have no chance of accidentally making contact with the conductors. The cable line, though free from the chances of contacts, is more liable to be broken mechanically; since the weight of the insulating material, and the larger surface exposed to the wind add considerably to the strains on the conductor, unless the latter is relieved by a special steel bearer wire being run from which the cable is suspended at short intervals.

The materials required for an overhead line, in addition to the conductors, are poles of wood or iron, insulators, bearer wires, struts and stay wires, and lightning guards. When bare, the conductor is generally of hard drawn copper, or silicon bronze; these materials giving, as we have seen in a preceding chapter, better results than steel or iron, when conductivity, breaking strain, and weight are all taken into account. Hard drawn copper can be obtained with 97 per cent. of the conductivity of pure copper, its breaking weight is 64,000 a, or 50,000 d^2 pounds, where a is the area and d is the diameter of the wire in

inches; and its weight is equal to 3·86 a, or 3·03 d^2 pounds per foot run. When insulated the conductor is most generally a soft copper wire or strand, in which case, except for very short spans, the strain should be taken off the copper, and should be borne by a separate bearer wire, which is generally a strand of galvanized steel wires weighing say 3·4 a pounds per foot run, and having a breaking strain of 90,000 a pounds, where a is the area of the strand in square inches.

The best wood for poles is the Norway red fir, although larch and Scotch fir are also employed. It is usual to specify the dimensions required, and that the poles shall be winter felled, and contain the natural butt of the tree, sound and hard grown, straight, free from large knots and other defects, and that they shall have the bark completely removed. Poles from 20 to 30 feet long should not be less than 5 inches diameter at the top, and from 7 to 9 inches at the ground line, that is say, 5 feet from the butt end; and they should always be creosoted to preserve them. According to the results of experiments carried out by the Post Office authorities, in 1885, at their Gloucester Road factory, the strength of such poles is given by the formula $P = 63{\cdot}7\frac{D^3}{L}$, where D is the diameter of the pole in inches at the ground line, and L the distance in feet from the ground to the point at which the resultant strain P is applied; and this value divided by a factor of safety of from 4 to 6 will give the safe working pressure. When iron poles are used they are generally made with a cast-iron lower tube, into which is fitted a tapered tube of wrought iron; or when the poles are much more than 20 feet long over all, two wrought-iron tubes socketed into one another are fitted to the cast-iron tube. In some cases a buckled plate

of wrought iron (see fig. 60) is attached to the base of the cast iron tube, so as to add to the stability of the pole when set in the ground; or the tube may be

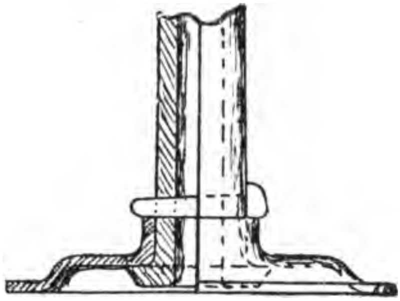

FIG. 60.

fitted with two cross-bars set at right angles to one another (see fig. 61); whilst in others the cast iron tube is made with a pointed shoe at its lower extremity, so

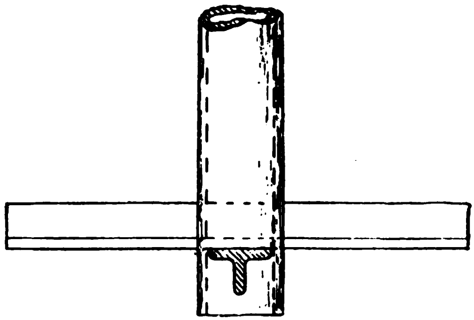

FIG. 61.

as to form a pile, which may be driven into the ground without first digging a hole to receive it (see fig. 62). When the line is straight, and the locality one which

is free from strong gales of wind, the stability of the pole as set in the ground is generally sufficient; but when it is subjected to considerable side strains from wind pressure, or from change of direction of the line wire, it is necessary to stiffen it by providing struts or stays, so placed that their point of attachment to the pole is as near as possible to the point at which the

FIG. 62.

resultant pressure is applied, and that the line along which this pressure acts is in the plane passing through the pole and stay, or strut. Good anchorage must be provided for a stay to prevent it from pulling out, and this is often obtained by attaching the lower end to a baulk of timber buried in the ground; it is also advisable to bury a flat stone or piece of timber under the foot of a strut, to give a larger bearing surface, and prevent it from being driven into the ground. For housetop lines iron poles are generally used, and are fitted into saddles placed on the ridge of the roof, so that the downward pressure may be distributed over

a large surface (see fig. 63). Poles fixed in this manner have no stability in themselves, but must be stayed in three or more directions, the downward pressure of the stay, and their own weight and that of the line, all combining to hold them firmly in place in the saddle. The strength of iron poles may be varied within very wide limits, according to the relative values given to their length and diameter, and to the thickness of metal: and it may be taken that the

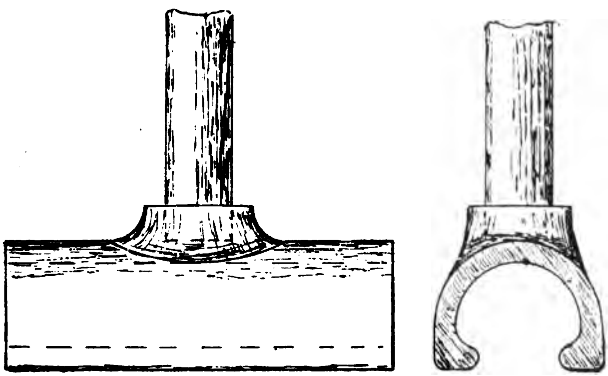

FIG. 63.

following expression will give a safe working pressure applied near the top of the pole, viz.: $P = 80\frac{D^4 - d^4}{DL}$

where P is the resultant pressure in pounds,

D and *d* are the outer and inner diameters in inches of the wrought iron tube at its base, and

L is the distance in feet from the ground line to the point at which the resultant pressure is applied.

The wires, whether bare or insulated, are generally supported on porcelain insulators of one or other of three types, viz.: the ordinary double-bell insulator, the

shackle insulator, or the oil insulator. The porcelain should be dense and of fine grain, uniform throughout, and free from cracks or flaws, and should be glazed all over. The double-bell insulator, as ordinarily made, is shown in fig. 64, and has grooves at the top and at the

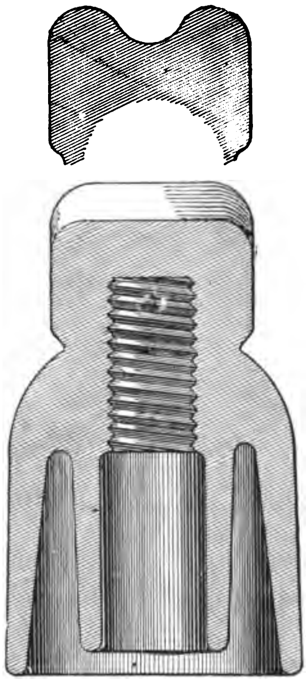

FIG. 64.

side; but the former is rarely used, the wire being laid in the side groove and fixed by lashings passing round the insulator in this same groove. The oil insulator is similar in many respects to it, but the bell is formed into a cup, as shown in fig. 65, and this cup is filled with oil, to diminish the amount of surface leakage.

The insulator is fitted with a bolt which is cemented in place, and is attached to a bracket fixed to the pole in the manner shown in fig. 66, which represents a method of attachment frequently used with wooden poles.

The shackle insulator (fig. 67) is used when the strain in the wire is considerable; as, although much inferior to either of the forms already mentioned as regards its insulating qualities, it is better adapted from

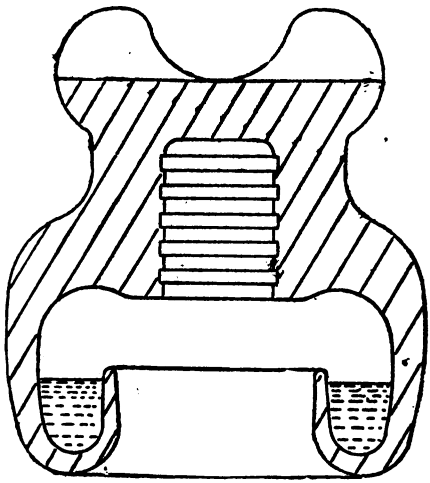

Fig. 65.

a mechanical point of view for withstanding the pull from the wire.

It is carried by two straps attached to it by a bolt passing through it from end to end, and the straps themselves are carried by a bracket or clip fixed to the pole.

Overhead lines are exposed to the chance of being struck by lightning, and precautions must therefore be taken to prevent injury from this cause to the line or apparatus connected to it. To protect the line, a

lightning rod is carried up some distance above the top of the pole, and is efficiently connected to the earth at its lower extremity; and, in addition to this, when

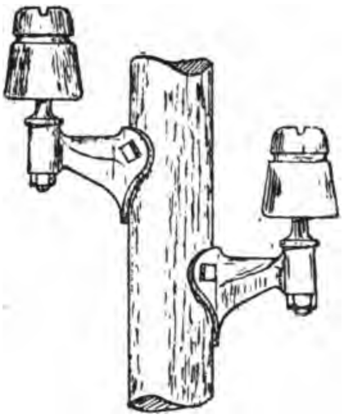

FIG. 66.

bare wires are used, a branch rod is arranged for each insulator, so that its point is within a very short distance of the wire. To protect the dynamos and

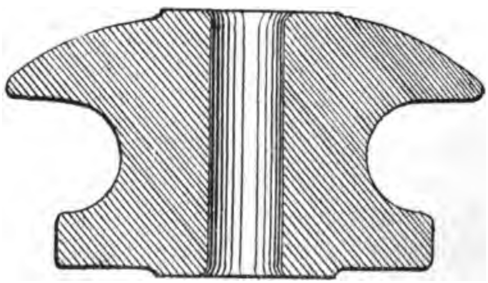

FIG. 67.

other apparatus, lightning protectors are fixed in the line on both the outgoing and return conductors, and are arranged in such a way that a small air gap sepa-

rates the line wire from an earth connection; this gap being somewhat greater than the sparking distance in air for the pressure employed on the line, but small enough to allow of the lightning discharge leaping across it. In England, where we are not so subject to violent storms as in many other countries, comparatively little attention has been paid to the design of protectors,

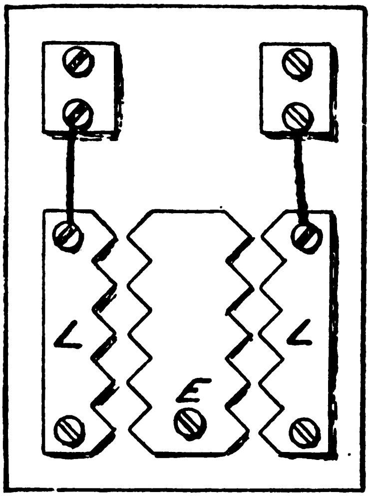

FIG. 68.

which will, after allowing the discharge to pass, automatically break any connection to earth caused by the maintenance of an arc by the working pressure. Fig. 68 shows a simple form of protector which may be used when no automatic circuit-breaking apparatus is necessary, the two plates being shaped so that there are several projecting teeth on each of them which approach one another very closely.

In America, where high-pressure overhead lines are numerous, and severe storms more frequent, several

very ingenious forms of lightning protectors are in use, which break the earth connection as soon as a discharge has taken place, and still leave the apparatus in working order and ready for another discharge, should one come. The best examples of American practice are the lightning protectors used in conjunction with the Thomson-Houston and Westinghouse systems; the former type depending for breaking the arc on the repelling effect on it of an electro-magnet, whilst the latter depends on the action of an air blast produced by the expansion of the air in a closed chamber, which results from the heat of the arc itself. The protector used by the Thomson-Houston Company on their arc light circuits consists of an electro-magnet in series with the arc lamps, and two insulated metallic plates, which are curved in such a manner that they approach very close to one another at their lower extremities, but that the distance between them gradually increases, (as shown in fig. 69,) towards their upper extremities. One of these apparatus is placed in the positive, and one in the negative line wire, between the overhead line and the dynamo terminals; the wire from the dynamo being connected to the bottom left-hand terminal, so that the current passes round the magnet coils and thence to the plate L, to which the line wire is attached. The other plate, E, is connected to the earth. If the line is struck, the discharge leaps across the small gap between L and E, and so gets to earth, in preference to passing through the coils of the electro-magnet; but the arc thus formed, if maintained by the high pressure employed on the circuit, is then in the magnetic field between the two pole-pieces, and is repelled upwards toward the part where the air gap is much greater, and is thus extinguished. The protector used by the same Company on high pressure trans-

former circuits is somewhat similar in principle; but the electro-magnets are not in the main circuit, but in the discharge circuit. To protect a transformer, the line wires are brought to two terminals, from which they pass on to the transformer. To each of these terminals is connected one end of the coil of an electro-magnet,

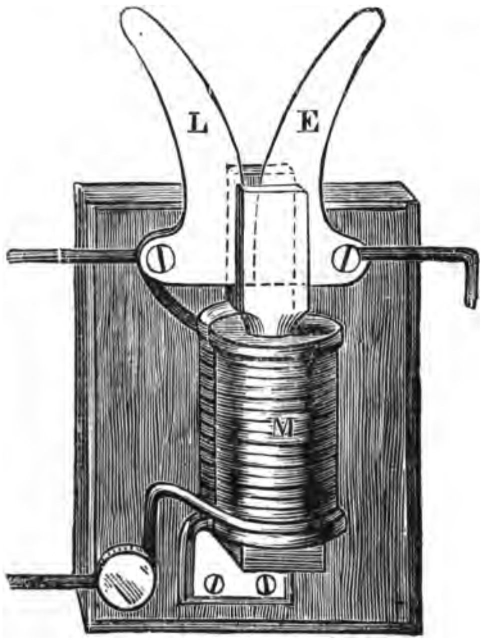

FIG. 69.

the other end being attached to a terminal in close proximity to a plate which is connected to earth. If the line is struck, the discharge passes through the coil and jumps the gap between the terminal and the earth-plate, this gap being so placed that the magnetic field, due to the current round the magnet coil blows out the arc.

The Westinghouse arc light circuit protector is shown in fig. 70: B is a carbon ball connected to

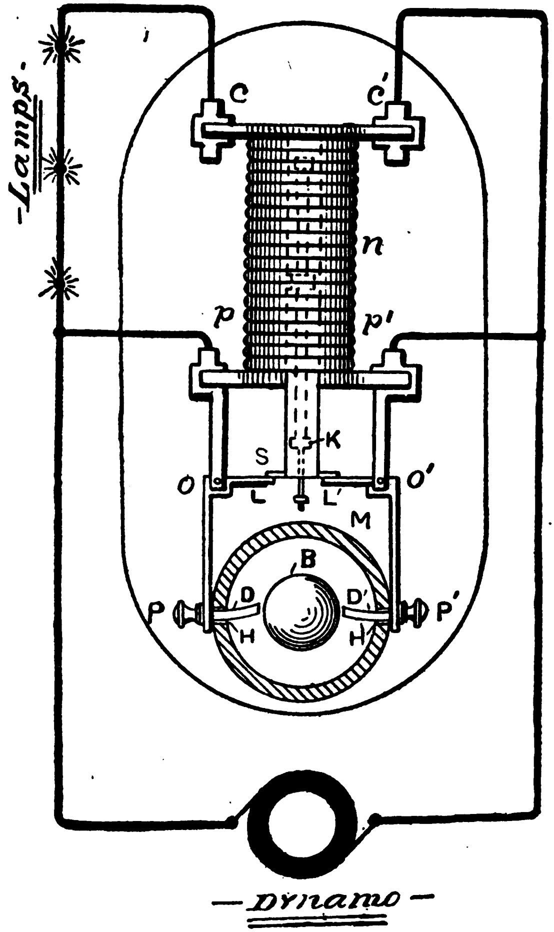

FIG. 70.

earth, and enclosed in a box M, through the walls of which enter two electrodes, D, D′, each of which is

carried on a bell crank pivoted at O, O′, and is separately adjustable by means of thumbscrews P, P′, by which the distance between the point of each electrode and the carbon ball can be regulated at will. A solenoid *n*, whose coil is in series with the arc lamps, is so placed that, when no current flows round it, its core, K, drops on the short arms, L, L′, of the bell cranks, and, by depressing them, draws the electrodes further away from the carbon ball. If the line is struck, the discharge passes through the terminals *p*, *p′* to the electrodes, and jumps the gaps separating them from the carbon ball. If the arc is maintained by the dynamo current, the solenoid is short-circuited; its core drops, and, striking the arms L, L′, separates the electrodes and the carbon ball by a greater air space. The heat generated by the arcs thus formed causes the air in the closed chamber to expand, and forms a blast, which escapes through the holes H, H′, and blows out the arc. As soon as the arc is broken, the current passes once more round the solenoid, and causes the core to rise, allowing the electrodes to take up their normal position again.

The protector used by the Westinghouse Company on their transformer circuits consists of two closed boxes *a*, *a′* (fig. 71), each of which has an opening, *c*, *c′*, leading into the tubes *d*, *d′*, and contains two carbon points, *h*, *i* and *h′*, *i′*, separated from one another by a gap of about one-eighth of an inch. Just above the opening leading into each tube is placed another pair of carbons, *f*, *e* and *f′*, *e′*, separated by similar air gaps, which are however short-circuited by carbon balls, *j* and *j′* The carbons *i*, *h′* are connected to the earth; *h* is connected through the carbons *f*, *e* and the ball *j* to one line wire; and *i′* is connected through the carbons *f′*, *e′* and the ball *j′* to the other line wire. If the line is struck, the discharge passes by way of the upper sets

of carbon points and balls to the lower carbons, and jumps the air gaps, thus passing to earth. The heat, due to the arcs formed at o, o', expands the air in the

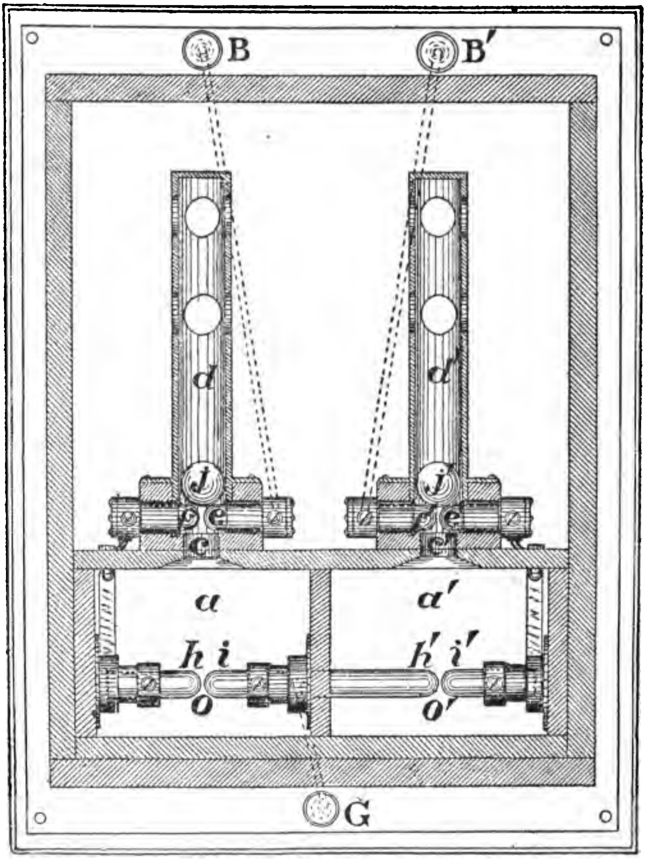

FIG. 71.

closed chambers, and the blast due to this expansion forces the carbon balls upwards in the tubes, and breaks the connection with the line wires. As soon

as the arc is broken, the carbon balls fall back into their normal positions, and once more complete the connection between the line wires and the carbons h, i', so that the apparatus is ready to act again should another discharge occur.

When designing an overhead line, it is necessary to consider the mechanical strains to which the line and its supports will be subjected, as well as the current-carrying capacity of the conductor and its insulation. The size of the conductor for an overhead line must be determined in the manner already explained; that is, in accordance with the law of economical current density, except when the conditions of working are such that the size of the conductor must be settled by its current-carrying capacity, or by the fall of pressure along it. The insulation may be effected by supporting a bare wire on porcelain insulators, or by using a continuously insulated conductor, which may be suspended direct from the insulators, or from special bearer wires. As we have already seen, the bare wire is only admissible when the line can be so placed that there is practically no chance of any person, or of any other wire making an accidental contact; and therefore such lines are rarely used in England, although many examples of them may be found in other countries. They are especially useful when power has to be transmitted some distance across country, as the cost of insulated cables would often be so great as to prevent the erection of the line. Wood or iron poles may be used with the ordinary double-bell or the oil insulator carried on brackets fixed to the pole. The two lines should be carried one on each side of the pole, as shown in fig. 72, and one at a higher level than the other, so as to prevent the two wires from swaying into contact when set in motion by the wind.

Continuously insulated conductors are often erected in exactly the same manner; and where the spans need

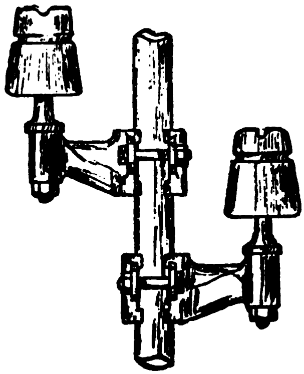

FIG. 72.

not be very long, and the line is not in an exposed position, this method answers very well. The bell-shaped insulators are however sometimes replaced by

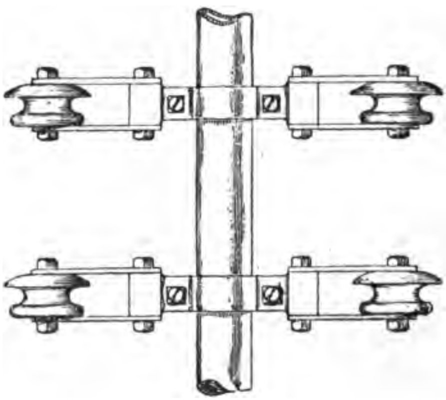

FIG. 73.

shackle insulators, which are then arranged as shown in Fig. 73. This plan would be objectionable when

bare wire is used, as the leakage is much greater with these insulators than with those of the double-bell type.

For housetop lines, where the spans are often of considerable length, owing to the difficulty of obtaining wayleaves, and the necessity of crossing wide streets, and where the line is more exposed to the wind, the insulated conductor is generally supported by ties from

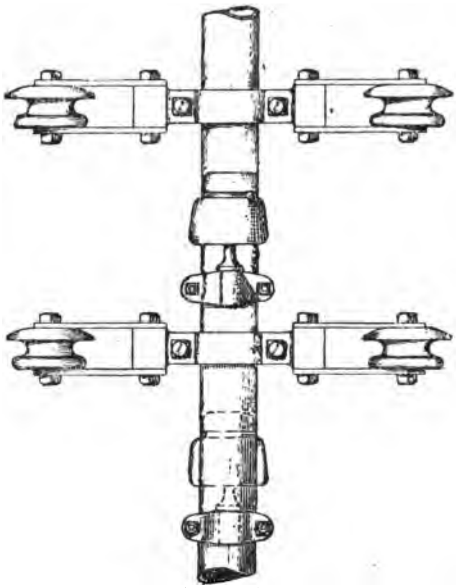

Fig. 74.

a bearer wire; these ties being placed at intervals of about 3 feet. When the bearer wire is attached to insulators, as is generally the case, shackle insulators are used, arranged as shown in fig. 74, the cable being attached to an insulator fixed at the side of the pole. The bearer wire, although increasing the cost, is necessary for all housetop lines, as it relieves the cable from all tensile strain, and greatly diminishes the

chance of a break in the conductor, an accident which might have serious results in large towns.

Another advantage of the use of a bearer wire is, that it does away with the strain on the cable at the points of support, and consequently diminishes the chance of damage to the insulation at that place; a chance that must always exist even with the most careful erection. We said that the bearer wire was generally attached to insulators, and this had to be done wherever the line was put up in accordance with the original Regulations of the Board of Trade; but it is by no means certain that this way of erecting the line is the best, and the 1896 Regulations of the Board of Trade, although they do not specify that the bearer wire shall be earthed, no longer insist that it shall be attached to insulators. The avowed object of insulating the bearer wire is to add additional insulation in series with that of the cable; and it certainly may allow of a line being worked when the cable itself is faulty; but this, instead of being a real advantage, may often be the exact opposite. The outer covering of tapes or braiding becomes a very fair conductor in wet weather, as also do the suspensions by which the cable is hung from the bearer; and consequently, if there is a fault in the insulation of the cable, the braiding, suspensions, and bearer wire may all be put in electrical connection with the conductor, with the result that a contact with any of them is equivalent to a contact with the conductor itself. Even if the insulating covering of the cable is perfect, an unpleasant shock may be got by contact with its outer surface, and in damp weather, therefore, from the bearer wire also; indeed, the bearer wire, being a good conductor and connected at frequent intervals to the cable by semi-conducting material, becomes equivalent to a metallic sheathing; and it is

universally recognised that any metallic sheathing on a cable working with high pressures must be earthed. The conditions under which a shock may be received from contact with the outside covering of the cable have been referred to in Chapter VII., where some figures were given showing that the current passing might be dangerously great. It is therefore much better to use a cable insulated in such a manner as to render the supplementary insulation of the bearer wire unnecessary, and to connect this latter to earth. Besides the advantages already mentioned, the earthing of the bearer wire would render it a sort of lightning protector for the line, as there would always be just above the cable an easy path to earth; and further, it would make the attachment of the wire to the pole a stronger and easier job mechanically, and it would somewhat reduce the cost of erecting the line.

We must now consider the mechanical strains to which an overhead line may be subjected, and the laws which govern them. When a wire is suspended between two poles, the tensile strain tending to break the wire is due, partly to its own weight, and partly to thepressure of the wind on its surface; it is greater as the span or distance between the poles is increased, and less as the sag or dip of the wire is increased. The law which determines the strain at the point of support, and this is where the greatest strain occurs, is as follows, $\frac{t}{w}=\frac{a^2}{8d}+\frac{7d}{6}$; which, when the dip is not excessive, may be simplified to $t=\frac{a^2w}{8d}$, where

t = strain at insulator in pounds
a = span in feet
d = dip in feet
w = resultant pressure in pounds per foot run.

The resultant pressure has for its two components

the weight of the wire per foot = W, and the pressure of the wind per foot = P; and as these two forces act at right angles to one another, since the direction of the wind is supposed to be along a horizontal line, we may write $w = \sqrt{W^2 + P^2}$. The direction of the wind is taken at right angles to the axis of the wire, as this direction gives the maximum strain of any, the value of P being calculated from $P = \cdot 05pd$, where p is the pressure in pounds per square foot on a plane surface at right angles to the direction of the wind, and d is the diameter of the wire in inches. The constant ·05 contains a coefficient, which represents the ratio of the effective pressure on a cylindrical surface to that on a plane surface; and for this coefficient the value 0·6 has been taken as a fair mean of the values which have been assigned to it by different writers, the exact value being somewhat doubtful from the want of accurate experimental data.

The formula given above may be written $d = \frac{a^2 w}{8t}$, or $a = \sqrt{\frac{8dt}{w}}$; and it is in one or other of these forms that it is of most use, as the values of t and w are fixed when the size and material of the conductor is decided; and, with these data given, we have to find, for a given span, what dip must be allowed, or, for a given maximum dip, what is the longest span that can be safely used.

The strains on the poles are a crushing strain due to the weight of the wire, and to the vertical component of the tension in the stays, if there are any; and a bending strain due to the pressure of the wind on the wires and pole, to a change in the direction of the line, or to the pull of the wires in two adjacent spans

being unequal. The crushing strain due to the weight of the wires is equal to the sum of the products aW for each wire; and that due to any stay wire is equal to the product of the tension in the stay into the cosine of the angle it makes with the pole. The side strain due to wind pressure is equal to the sum of the products aP for each wire, plus the pressure on the surface of the pole, which equals ·05pD multiplied by the length of the pole in feet. The side strain due to a change in the direction of the line is most easily obtained by drawing a parallelogram of forces; but, in the usual case, where the tensions t and t' in the two neighbouring wires are equal, the strain $= 2t \cos \frac{a}{2}$, where a is the angle enclosed by the two wires at the support. The strain at a terminal post, or at a pole where the tensions in the two wires are unequal, is obtained by calculating the value of t for each wire and taking the difference between them.

In any of these cases, if the resultant pressure tending to bend the pole is greater than $15 \frac{D^3}{L}$ for wood poles, or $80 \frac{D^4 - d^4}{DL}$ for tubular iron poles, stays must be fixed to stiffen them; and these stays should be attached as near as possible to the point at which the resultant pressure acts, and in the same vertical plane with it. The strain in the stay wire will be equal to the resultant pressure, divided by the sine of the angle between the pole and the stay wire, if the latter is attached to the pole at the point at which the resultant pressure acts; and if not, but at a height L′ above the ground, then the value given above must be multiplied by $\frac{L}{L'}$.

Let us consider an example of a bare wire line, of a

cable line without bearers, and of a cable line with bearers: first, on the assumption that a wind pressure of 20 pounds per square foot is to be allowed for, and that the usual factor of safety of 4 is to be used; and then that the wind pressure is 50 pounds per square foot, and that factors of safety of 6 for the line and 12 for the supports are to be used, these latter figures being those that are specified in the regulations drawn up by the Board of Trade.

Bare wire line of two conductors, each of 7 strands of No. 16 L.S.G. hard-drawn copper. The area of this conductor is ·0225 square inches, and the diameter ·192 inches. The weight per foot run $W = 3{\cdot}86 \times {\cdot}0225 = {\cdot}087$, and the safe working tension with a factor of safety of 4 is $t = \frac{64000 \times {\cdot}0225}{4} = 360$. The wind pressure per foot run $P = {\cdot}05 \times 20 \times {\cdot}192 = {\cdot}192$, when $p = 20$ lbs. per square foot. $w = \sqrt{W^2 + P^2} = \sqrt{({\cdot}087)^2 + ({\cdot}192)^2} = {\cdot}211$. If we take a span of 200 feet, the dip will be $d = \frac{200 \times 200 \times {\cdot}211}{8 \times 360} = 2{\cdot}93$, or say 2 feet 11 inches. It must be remembered that this is the minimum dip that can be allowed with safety; and therefore the wire should be strained so that, at the lowest temperature it is likely to reach, there will be this amount of dip. At higher temperatures the dip will be greater, owing to the expansion of the wire; and this should be taken into account, if the line is fixed when the temperature of the atmosphere is not at its lowest. This may be done by calculating the length of the wire in the span by the formula $s = a + \frac{8d^2}{3a}$, and adding to it the number obtained by multiplying it by the coefficient of expansion per degree, and by the number of degrees that the temperature is above the minimum. With this new value s' we can then calculate the dip d' from

the same equation, which may also be written $d' = \sqrt{\frac{3a(s'-a)}{8}}$. For example, suppose that a fall of temperature of 40° Fahr. is to be allowed for; the coefficient of expansion for copper being $\frac{9 \cdot 56}{10^6}$, we should proceed as follows:—

$$s = 200 + \frac{8 \times (2 \cdot 93)^2}{3 \times 200} = 200 \cdot 115$$

$$s' = 200 \cdot 115 + \left(200 \cdot 115 \times 40 \times \frac{9 \cdot 56}{10^6}\right) = 200 \cdot 191$$

$$d' = \sqrt{\frac{3 \times 200 \times \cdot 191}{8}} = 3 \cdot 79, \text{ or say 3 feet } 9\tfrac{1}{2} \text{ inches.}$$

The side strain at the point of support is equal to $2aP = 77$ lbs.; and if we employ a wood pole of 6 inches diameter at the ground line and 5 inches diameter at the top, and standing 21 feet out of the ground, the pressure due to the wind on the pole itself will be $\cdot 05pD'L = 116$. This pressure may be taken as if it acted at a point 10 feet above the ground, and the strain due to the wires as applied at a point say 20 feet above the ground.

The resultant bending moment $(77 \times 20) + (116 \times 10) = 2{,}700$ pounds at one foot, or somewhat less than that which the pole we are using can safely stand, which is equal to $15D^3$ or 3,240 lbs. at one foot.

If now we increase the wind pressure to 50 lbs., and allow a factor of safety of 6, we get the following values:—

$$P = \cdot 05 \times 50 \times \cdot 192 = \cdot 480 \therefore w = \sqrt{P^2 + W^2} = \cdot 488$$

$$t = \frac{64000 \times \cdot 0225}{6} = 240.$$

These figures give a dip of about 10 feet for a span of 200 feet, which is more than can generally be allowed at minimum temperature. We must then shorten the

span, and if we assume a dip of 5 feet we get for the maximum span, $a=\sqrt{\dfrac{8\times5\times240}{\cdot488}}=140$ feet.

The side pressure at the point of support $=2aP=2\times140\times\cdot480=135$ pounds, which gives a bending moment of 2700 at the ground line. The 6-inch pole will not be strong enough, especially as we have to allow a factor of safety of 12, which reduces the safe bending moment to $5\ D^3$ instead of $15\ D^3$; and we shall find that the pole must have a diameter of about 12 inches, which safely allows of a bending moment of 8640. The pressure of the wind on the pole itself will be $\cdot05\times50\times11\times21=577\cdot5$ and the resultant bending moment will be $(135\times20)+(577\cdot5\times10)=8475$.

Cable line of two conductors, each of 7 strands of No. 16 L.S.G. soft copper, insulated and braided to a diameter of ·430, and without bearer wires. Wind pressure 20 pounds per square foot. $W=\cdot158$, $P=\cdot430$, $w=\cdot458$, $t=169$. In this case we shall again find that for a span of 200 feet the dip will be considerably over 5 feet; so we will find the maximum span for this dip, which is $a=\sqrt{\dfrac{8\times5\times169}{\cdot458}}=121$ feet.

The side pressure at the point of support $=2aP=2\times121\times\cdot430=104$ lbs., which gives a bending moment of 2080. A 6-inch pole will be required, which will allow of a bending moment of 3240, and will add one, due to the pressure of the wind on itself, of $10(\cdot05\times20\times D'L)=1160$, giving a total bending moment of $2080+1160=3240$.

For a similar line, when the wind pressure is 50 lbs. per square foot, and the factor of safety 6, we get $W=\cdot158$, $P=1\cdot075$, $w=1\cdot09$, $t=112$, and a dip of 5 feet will only allow of a span

$$a=\sqrt{\frac{8\times5\times112}{1\cdot09}}=64\text{ feet.}$$

The side pressure at the point of support $= 2aP = 2 \times 64 \times 1{\cdot}075 = 138$, which gives a bending moment of 2760. A 12-inch pole will be required, which will allow of a bending moment of 8640, and will itself add one of about 5775, so that the total bending moment will be 8535.

Cable line as above on housetops, and with bearer wires of 7 strands of No. 14 steel wire. For the cable $W = {\cdot}158$, $P = {\cdot}430$, and for the bearer wire $W' = {\cdot}120$, $P' = {\cdot}240$, $t = 22500 \times {\cdot}0352 = 792$. The resultant pressure on the bearer wire is $w = \sqrt{(W + W')^2 + (P + P')^2} = {\cdot}726$, therefore for a span of 200 feet

$$d = \frac{(200)^2 \times {\cdot}726}{8 \times 792} = 4{\cdot}58 \text{ feet.}$$

The side pressure at the point of support $= 2a\,(P + P') = 400 \times {\cdot}670 = 268$. In this case we do not need to use a pole of sufficient strength to stand the strain by itself, as stay wires must be used; and we may therefore suppose that a pole 15 feet long over all, and $3\frac{1}{2}$ inches external diameter, is used; and also that the resultant pressure acts at a point one foot from the top, and that the stay wires are attached a foot below this. The pressure of the wind on this pole will be $({\cdot}05 \times 20 \times 3{\cdot}5 \times 15) = 52{\cdot}5$ lbs., acting at a point 7·5 feet from the heel of the pole, and the resultant pressure at the point of attachment of the stay wire will be $\left(\frac{268 \times 14}{13} + \frac{52{\cdot}5 \times 7{\cdot}5}{13}\right) = 318$ lbs.

If the stay wire makes an angle of 45° with the pole, the tension in it will be $\frac{318}{\sin\ 45^\circ} = 450$ lbs., which will require a wire of 7 strands of No. 16.

The weight to be carried by the roof is the sum of the weights of the span of double line, the pole and saddle, and the vertical component of the

tension in the stay wire. The weight of the line is $2a(W + W') = 112$ lbs., and that of the pole and saddle about 180 lbs.; and the vertical component of the tension in the stay wire $= 450 \cos 45^\circ = 318$, giving a total of 610 lbs.

For a similar line, when the wind pressure is 50 lbs., and factors of safety of 6 and 12 are used, we get $W = \cdot 158$, $P = 1\cdot 075$, $W' = \cdot 120$, $P' = \cdot 600$, $t = 528$, $w = 1\cdot 7$. With a dip of 5 feet $a = \sqrt{\dfrac{8 \times 5 \times 528}{1\cdot 7}} = 111$ feet. The side pressure on the line $= 2a\ (P + P') = 222 \times 1\cdot 675 = 372$ lbs. and that on the pole $= 131$ lbs., giving a resultant pressure at the point of attachment of the stay equal to $\dfrac{(372 \times 14) + (131 \times 7\cdot 5)}{13} = 476$ lbs.

The tension in the stay wire $= \dfrac{476}{\sin 45} = 673$ lbs., which, with a factor of safety of 12 will require a wire of 19 strands of No. 14. The weight to be carried by the roof $= 62 + 180 + 476 = 718$ lbs.

If it were necessary to use a span of 200 feet with a dip of 5 feet, a very large bearer wire would be required, as the values of W' and P', and consequently that of w, increase with the size of the bearer. The actual wire required would be 19 strands of No. 12, for which $W' = \cdot 549$, $P' = 1\cdot 300$, and $t = 2420$. This would give $w = 2\cdot 48$, and therefore if $a = 200$, $d = \dfrac{(200)^2 \times 2\cdot 48}{8 \times 2420} = 5$ feet $1\frac{1}{2}$ inches. Such a line is altogether impracticable, as the pressure on the roof and the pull on the stay wires would be so great that there would be much difficulty in finding suitable places to fix the poles. The tension in the stay wire would be about 1,480 lbs., and the downward pressure due to it would be 1050 lbs. The weight of the line would be 283 lbs.,

which, with that of the pole and saddle, would bring the total pressure on the roof up to about 1,600 lbs.

We see from these examples how great a difference is made by a change from 20 to 50 pounds per square foot for the wind pressure; and although the extra cost of the line should not deter any one from fixing it, if there is any probability of such a pressure being brought to bear on it, yet the enforcing of this specification appears to be unnecessary, as it is doubtful whether a pressure even approaching to 50 lbs. per square foot has ever been registered in any of our large towns, and it is pretty certain that there is hardly a roof in London that has been designed to stand such a wind pressure. Mr. Preece, in a paper "On the Strength of Round Timber," read at the meeting of the British Association in 1885, stated that the experience of the Post Office showed that a fair average figure for the wind pressure was 18·75 lbs. per square foot; and many overhead electric light lines, which have been in use for some years without suffering, even at times when the telegraph and telephone wires have been blown down, have apparently been calculated for 20 lbs. wind pressure.

CHAPTER XIV.

Underground Lines.—Bare Wire Mains.—Built-in System.—Drawing-in System.—Accumulation of Gas in Conduits and Boxes.—Conduits.—Brick and Concrete Culverts.—Earthenware Conduits.—Iron Pipes and Troughs.—Bitumen Concrete Conduits.—Wood Conduits.—Manholes.—Joint Boxes.—Method of Laying Cables.—General Arrangement of Mains.

ALTHOUGH overhead wires may often be used with advantage, more especially for the transmission of electricity over long distances; it will be found that, as a general rule, the use of an underground main is more satisfactory for the distribution of the current; and in England it is the only method which is allowed in any of the large towns. As with overhead wires, the insulation may be provided by supporting a bare conductor on glass or porcelain insulators, or by entirely covering the conductor along its whole length with insulating material; the former method being only employed with low pressures, and the latter with both low and high pressures.

In all bare wire systems a culvert must be constructed in such a manner as to keep out water as much as possible; and, as it is impossible to do this entirely, provision must be made, by connecting the culvert with the drains, for carrying off any water that may collect in it. In this culvert, insulators of porcelain or glass are fixed at regular intervals, and on them are supported the conductors, which consist of bare copper strips.

The advantages claimed for this method of insulation are, that the sectional area of the conductor may be increased within wide limits, without at the same time

materially increasing the cost of insulation; that the materials employed are not liable to much depreciation; and that connections between feeders and distributing mains, and between these latter and the house service wires, can be easily made, since the joints are only copper joints and have not to be insulated. The disadvantages are that the first cost of the culvert is considerable, and for small sectional areas of copper out of all proportion to the cost of the copper; that the culvert occupies a much larger space under the footways than can in very many cases be devoted to electrical mains, and this necessitates the use of continuously insulated cables alternating with lengths of bare strip; that the insulation resistance of such a system is by no means high, and is liable to considerable variation; and that there is always the unpleasant prospect of a serious breakdown, should the culverts get flooded by the bursting of a drain or water main.

As regards economy, both in first cost and cost of up-keep, too much has sometimes been claimed for bare wires underground; as, although they are decidedly cheaper to lay down than insulated cables when the joint area of the conductors is very large, there is not much difference in cost between the two methods for the areas usually required for distributing mains. For up-keep, an annual charge of 1 per cent. has been proposed as an ample allowance for bare mains, but this appears to be too little. It is difficult to get accurate figures, as practically no complete network of bare copper mains exists; so that the only comparison we can make is between systems which employ insulated cables only and those which use bare copper mains mixed with cables. A reference to the table of expenditure on mains of a number of undertakings (see Appendix B) shows that the average cost of wages

and renewals for insulated cable systems comes to 1·42 per cent. of the capital expenditure, whilst for systems in which bare mains and cables are employed this figure is 1·72 per cent.

The bare wire system is, however, very convenient for branching off service wires, and this tells very much in its favour; as also does the fact that many small faults may exist without interruption to the service, since the continued flow of the leakage current will often remove the fault instead of making it worse, as would be the case with an insulated cable. The loss of current may be considerable, and should be taken into account; but this is, in the opinion of the advocates of the system, far more than counterbalanced by the conveniences mentioned above. The possibility of the culvert being flooded is one of the most serious objections to the system, and that this is a real risk is shown by the fact that an accident of this kind has occurred to the mains of the House-to-House Co. at Kensington, through a water pipe bursting in a street through which their mains were laid. In this particular case no interruption of the service resulted, because the mains consisted of well-insulated cables laid in iron pipes; but had there been a culvert with bare copper in place of this, a serious breakdown must have occurred, which would not, in all probability, have been a local one only, as the culvert would have acted as a convenient drain for the water to run into, and would have been flooded for some considerable length. Such an occurrence fortunately does not happen often, but the risk is somewhat similar to that to which overhead lines are subject from heavy snow-storms or gales; and, as the inconvenience to the users of the current would be more felt than when the telegraph lines are interrupted, it is all the more incumbent on

the supply companies to avoid the chance of an interruption from such a cause.

When continuously insulated conductors are used, they may be laid in various ways, all of which, however, can be grouped into two classes; in one, the insulated conductor is built in, that is to say, is laid in such a manner that access to it can only be got by opening up the ground; and in the other, the cable is drawn into a pipe or conduit, from which it can also be withdrawn if necessary. When the built-in system is employed, the mechanical protection of the insulated conductor may be provided by iron or steel tubes, as in the Edison or Ferranti mains, by an armouring of iron wires or tapes laid up round the core, or by laying the cable in a trough filled up solid with compound.

The tubes or armoured cables are often laid direct in the ground, with a board or metal plate placed some few inches above them, to give warning of their presence to workmen who may have occasion to open up the ground for any purpose; or they may be laid in a boxing filled in with cement or asphalte. Another plan which is often employed is to lay the cables on bridges of wood in an iron trough, which is afterwards filled up solid with bituminous or other similar compound. In any case the cable must be laid in whilst the ground is open, which is often inconvenient; as the length of trench, which can be kept open at any given time, is restricted by the vestries or other road authorities. The cable on its drum is generally mounted on a trolly, which is wheeled along by the side of the trench, and as the cable pays off the drum, it is laid in place in the trench.

In the drawing-in system, the mechanical protection of the cable is provided by the pipe or conduit into

which it is drawn; this pipe or conduit being laid underground, and the trench filled in again, before the laying of the cable is commenced. There is therefore no need for armouring, or other such protection on the cable itself; and, in comparing the costs of a built-in armoured cable with an unarmoured one drawn into a pipe, the heavier cost of the armoured cable will be found to go a good way towards paying the cost of the pipe. Of course, when the built-in cable is laid in an iron trough filled in with bituminous compound, there is practically no difference in cost of mechanical protection, between it and a cable drawn into a pipe or trough, and therefore the choice of systems may be decided chiefly by considerations of convenience. From this point of view the drawing-in system is much to be preferred, since the cables can be drawn in or out without disturbing the surface of the road or pavement; whereas with a built-in cable, the ground must always be opened up, whenever it is desired to obtain access to the mains for repairs, or to increase the sectional area of the conductor. This opening up of the ground and making the surface good again is an important item in the cost of underground work, especially in towns, where expensive pavements, such as wood or asphalte, may have to be taken up and replaced, and the mains placed below the bed of concrete on which the wood blocks or asphalte are laid. This class of pavement is of course avoided wherever possible, and the mains laid under the footway, which is generally paved in London with York flags; but even with this pavement, which is about the cheapest we have to deal with, the expense of excavating, of temporarily replacing the flags, and of vestry charges for re-laying and for broken stones, will amount to four or five shillings per yard.

Let us consider the effect of this on the cost of increasing the area of the conductors to keep pace with an increasing demand for current. With a built-in system, unless we lay in the first instance conductors of sufficient area to meet the maximum possible demand, (and this would probably tie up more capital than could be afforded), we must incur the expense of opening up the ground at any time when we wish to extend; whereas, with a drawing-in system, additional cables may be drawn into the existing conduit, or the smaller cable may be withdrawn and replaced by a larger one, or, if spare pipes have been laid in the first instance, additional cables can be drawn in as the need for them arises. Now the extra cost of laying a 3-inch instead of a 2-inch pipe, or a 4-inch instead of a 3-inch pipe, that is to say in either case doubling the capacity of the conduit, is a shilling or less per yard for each way; so that for a three-wire system, with a separate way for each cable, the extra conduit space would only cost about two-thirds of the amount required for opening up the ground and making good again. With a two-wire system with both cables in the same pipe, an extra 3-inch pipe can be laid for about two shillings per yard, or a 4-inch for about three shillings; so that, when extensions are taken into account, there is really no economy gained by the use of a built-in system; whilst the convenience, both to the supply company and to the users of the streets, which results from its being unnecessary to disturb the surface, is very great.

With regard to the facilities afforded by the two systems for localizing and repairing faults, the advantage is again with the drawing-in system. The localizing of a fault is not a very easy matter on electric light circuits, and it is difficult to place it

within perhaps 20 yards or so; and, when this is the case, the built-in cable will have to be dug up for a considerable length, and examined until the fault is found; and this examination may necessitate the cutting of the metal sheathing, which very often does not show any external signs of damage. With a drawing-in system, if the fault is located within the same limits, the engineer knows that it is somewhere between two surface boxes, and he can therefore draw out the cable between these points, and replace it with a length of good cable; an operation which can be performed very quickly, and with the minimum of inconvenience to the traffic in the streets.

So far we have considered only the relative convenience of the two systems, but there is another important point that must not be overlooked, and that is whether there is less chance of faults occurring in one system than in the other. If we have a cable covered with a good quality of insulating material, carefully put on and tested before laying, the chief causes of faults are either mechanical damage or chemical action due to some foreign matter present in the surrounding soil. As regards damage during laying, the drawing-in system is at a disadvantage, as the cable is subjected to greater strains, and any damage done to the insulating covering can more easily escape detection owing to the cable not being in view. When once the cable is laid, the conditions are reversed; as armoured cables laid in the ground, or cables laid in a trough (unless the latter is of iron) are more liable to damage from the pick of a workman opening up the ground, than are cables laid in an iron pipe. As regards chemical action, the armoured cable laid in the ground, whether lead-covered or not, is

probably the most liable to damage; but there is not much to choose between it and the unarmoured cable laid in a pipe, unless the latter can be kept absolutely watertight, which is, in the author's opinion, practically impossible. The best method of protecting a cable from chemical action is to lay it in a trough filled up solid with a bituminous compound; and this method, which was first used by the Callender Company with their bitite cables, has been employed of late years with great success both with rubber cables and with the various types of lead-covered cables.

Another point which must be remembered is that the drawing-in or any conduit system is more liable to damage from explosions of gas than the built-in system. In the latter system it is only in the surface boxes that there is any space in which gas can accumulate, and to these it can only get access through the walls of the box itself; whereas in conduit systems, infiltration of gas may take place anywhere along the length of the conduit, and, unless measures are taken to prevent it, gas may pass along the conduit for a considerable distance. As it appears to be hopeless to expect that the gas companies will prevent leakage from their pipes, and as, especially in London and other large towns where asphalte, wood, and other impervious pavements are used, it is very difficult for gas to escape at the road surface, the presence of gas in the soil surrounding electric light mains is a factor that must be taken into account.

In conduits of considerable cubic capacity, such as are used for bare wire mains, an explosion is possible in any part of the conduit as well as in the boxes; in drawing-in systems for insulated cables where the cable

nearly fills up the way, there is very little chance of an explosion in the conduit, but gas may find its way in at any part of the conduit and so enter the boxes; and in the built-in system, gas may pass through the walls of the box, and then form an explosive mixture. Opinions differ very much as to the best measures of prevention; and though thorough ventilation is an easy thing to recommend, it is not so easy to decide on the particular way in which it is to be carried out. Ventilation by air chimneys and natural draught, or by any means which tend to reduce the pressure in the boxes or conduits, does more harm than good, unless provision is made by a system of inlet pipes for a corresponding indraught of air free from gas; otherwise the tendency will be to suck in more gas at the points where it has already entered. Ventilation by forced draught, so as to maintain a small pressure in the conduits, should be a perfect remedy; but it is costly and difficult to carry out on an extended system. It is, however, to be recommended for bare wire conduits where the capacity of the conduit is large enough to allow the formation of an explosive mixture anywhere along its length.

For the ordinary drawing-in system, the author considers that the following plan is the best, and that it will give perfectly satisfactory results. The sides and bottom of the box should be well cemented and made as impervious as possible to gas, and the ends of all pipes should be blocked up at each box so as to prevent the passage of gas from the conduits to the box. The boxes should be kept as small as possible, or their capacity should be reduced by partially filling them with incombustible material, and they should be regularly

inspected. The same precaution should be adopted for the boxes in a built-in system; and in all cases where gas is found to be present, the gas company should at once be notified, and frequent inspection should be made until the leak has been found and repaired.

From what has been said above, we see that the armoured cable laid direct in the ground is generally the cheapest in first cost, and is less liable to injury during laying than the cable drawn into a pipe; but that once laid, it is more easily damaged both mechanically and by chemical action, and that it has the great disadvantage of being inaccessible and of necessitating the opening up of the ground for extensions or for localizing and repairing a fault. The cable laid in a trough filled in solid with compound has the same disadvantage of inaccessibility, but it can be laid with little chance of injury and is better protected from chemical action than if laid on any other system; and if the trough is provided with an iron cover, the protection against mechanical injury is as good as that afforded by a cast-iron pipe. The drawn-in cable is generally dearer than the armoured cable laid direct in the ground, but cheaper than one laid on the solid system, and is well protected from mechanical injury after laying; but it is more liable to damage during laying and is not so well protected against chemical action as if laid on the solid system. It has, however, the great advantage of affording facilities for increasing the weight of copper in the mains as the need for it arises, and for repairing or replacing faulty lengths of cable without necessitating the opening up of the ground after the pipes are once laid.

Conduits for underground wires take many different forms, and may consist of concrete or cement lined brick culverts, metal or earthenware pipes or troughs, or casings made of prepared wood or of bitumen concrete. Brick or concrete culverts are but rarely used for cables, unless a number are to run, as they are more expensive and occupy more space than many other conduits. They must be divided up by longitudinal partitions into separate and distinct ways, so as to prevent the several cables from crossing or fouling

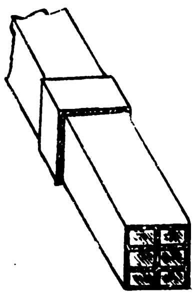

FIG. 75.

one another. They are, however, used in most of the bare wire systems; and are to be preferred to the iron troughs used by one or two companies.

Earthenware pipes or troughs were tried in England in very early days, some of the first telegraph lines consisting of gutta percha covered wires laid in earthenware pipes, the joints of which were made with clay; but they did not meet with much favour. The Lake conduit, however, has been extensively used by the United States Electric Light Company and others in America; it is made of the best stoneware vitrified and

glazed, which offers a very hard and smooth surface. The conduit is generally made with a number of separate ways, each shaped so as to take two cables (Fig. 75), and is delivered in short lengths, which are connected by stoneware covers set in cement. The great objections to the use of stoneware are its liability to fracture, and the difficulty of making good joints without making them so rigid that they will not adapt themselves to slight alterations of alignment due to the sinking of the ground or other causes. One of the troubles with the telegraph lines in which earthenware pipes with clay joints were used, was that roots of trees and other vegetation forced their way through the joints; and Mr. Fleetwood, in a paper read before the Society of Telegraph Engineers in 1887, mentions a case where a root forced its way in, and entwined itself round the cable in such a way as to hold it fast and prevent it from being withdrawn.

In England the use of stoneware conduits has again been introduced, chiefly owing to the attention which has been given by Messrs. Doulton & Co. to details of manufacture and methods of jointing, and there are now many miles of it laid down in London and the provinces. Doulton conduits are made of hard-burnt glazed stoneware, sometimes in the form of circular pipes fitted with self-adjusting joints, and sometimes in casing of rectangular shape containing two or more ducts, in which case they are jointed with Portland cement or with bituminous cement. The self-adjusting joint for pipes is made by casting a band of composition of a spherical form on the spigot, and a similar but cylindrical band inside the socket. When laying these pipes the spigot of one pipe is pushed into the socket of the other, and it is claimed that a good

mechanical fit is made without the use of cement, and this whether the two pipes are in the same line or make a small angle with one another.

The casings are laid under the footways or roadways, but in the latter case it is necessary to lay them at a depth of about three feet, or if nearer the surface to bed them in concrete. Portland cement joints are made by bedding the ends in cement on stoneware cradles, and then covering the upper part of the joint with

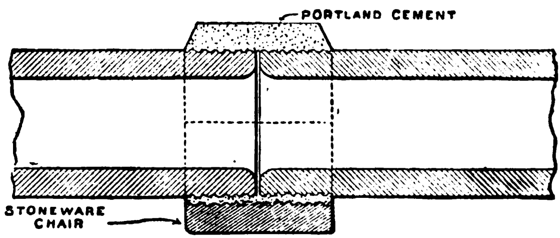

FIG. 76.

cement (as shown in Fig. 76), plugs of wood being inserted in the ducts to keep them in line, and to prevent the cement from getting into them.

When the bituminous cement joint is to be used, the lengths are laid with a shallow cast-iron bearer under the joint, and so that the two lengths do not butt up quite close. An expanding mandril is introduced into each duct to ensure proper alignment, and an iron mould, open at the top, is placed over the joint, into which is poured a quick-setting bituminous cement, which encloses the ends of the two lengths of casing,

and fills up the space between them, except where it is occupied by the mandrils. After a few minutes the cement is sufficiently set, and the mandrils can be withdrawn and the iron mould removed, leaving the joint as shown in Fig. 77.

In addition to the ordinary casings, others are made in which the stoneware during manufacture is partially divided longitudinally, so that the two parts can be separated, when necessary, by means of a chisel. These

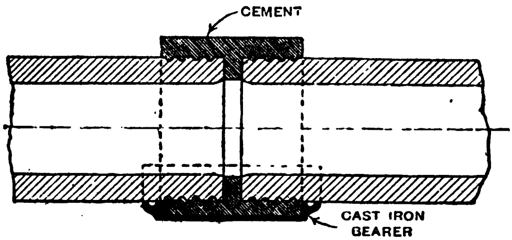

FIG. 77.

special casings are used to facilitate access to the cables for making services, and a length of casing may be split and removed, being replaced by a box in brick or stoneware, or by a special length of casing provided with a tee for leading away the service wires.

Stoneware culverts for bare copper mains have also been made and used instead of brickwork or cement ones, and have this advantage over the latter, that they can be laid and the trench filled in again in much less time.

Metal pipes or troughs, either of cast or wrought iron, are largely employed, and in New York some zinc tubes laid in hydraulic cement have also been used. When laid direct in the ground, cast-iron pipes are preferable to any other, as they are very strong and last much longer, when in contact with the soil, than wrought-iron pipes, even if the latter are galvanized or served with jute soaked in bitumen. The experience of the Post Office Telegraph Department has led them to adopt cast-iron socket pipes as the best and most convenient conduit; and as they, and their predecessors, have had them in use for over forty years, and have also tried split pipes, wrought-iron pipes and earthenware pipes, their decision is one which must carry great weight. In America wrought-iron pipes are generally laid in groups, embedded in asphalte concrete, or hydraulic cement; and the grouping is altered to suit the space available, the pipes being laid, sometimes in two or three rows one above the other, at other times spread out into one wide row. Zinc pipes are sometimes used instead of the ordinary iron pipes, as also are pipes made of sheet iron lined with cement. The grouping of the pipes and laying them in concrete has the great disadvantage that more space is occupied underground, and that the system is not so flexible as one in which the pipes are all independent, and can be shifted nearer or further from one another to get past the various obstacles which are met with underground; but it makes a strong and lasting job, and has been found to make a good conduit as regards gas-tightness, a matter of the greatest importance in many American cities, where the soil is saturated with gas to a very considerable extent.

The Callender-Webber casing consists of blocks of bitumen concrete, with two or more separate ways running lengthwise of the blocks (Fig. 78); each way being intended to take one cable. The joints between the lengths of the casing are made in the following manner:—The two lengths being in position, a long mandril is pushed through each hole in the length last laid, and into the corresponding hole of the block to which it is to be joined; and hot bitumen is poured over the joint, and rammed down so as to fill up the space between the two blocks, except where it is

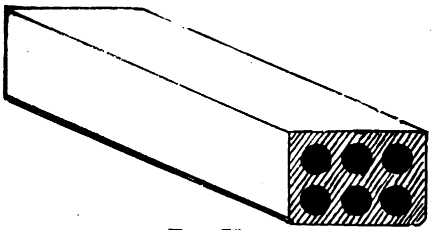

FIG. 78.

occupied by the mandrils. When the joint has cooled down, the mandrils are withdrawn, leaving smooth holes through the joint of the same diameter as the ways in each block. The casings are sometimes laid without further protection, and sometimes with an inverted iron trough placed over them so as to cover the top and sides, and protect them from injury from the picks of workmen.

The casing is strong enough to withstand any pressure to which it is likely to be subjected underground; a case being mentioned by General Webber, when replying to the discussion on his paper on the "Distribution of Electricity in Chelsea," where a steam

roller was at work, immediately after the casing had been laid about 30 inches under a Macadam road, and where the casing was therefore subjected to a good practical test, which it stood satisfactorily. At the same time General Webber stated that the material had the defect of being friable, and of not affording such good protection against injury as other forms of conduit when the ground about it was being excavated for any purpose, and further, that it was porous and susceptible to changes of temperature. Its porosity is of no great moment if a waterproof insulating covering is provided on the cable, as it always should be; but the softening at moderate temperatures is the cause of some inconvenience, since it is necessary to shift the cables periodically, as otherwise they adhere to the casing, and cannot be drawn out without considerable risk of injury.

A somewhat similar conduit is the Dorsett conduit, of which considerable lengths have been laid in America. The materials, of which the blocks are made, are coal tar pitch, and fine gravel; and the separate sections are jointed by inserting paper tubes which form sleeves connecting the ducts in the two lengths, and then pouring soft mastic in to fill the space between the lengths, and join them together. The reports of this conduit have not been favourable, as it is said to be porous, inelastic, and brittle; but many of the failures which are attributed to it, were due to the use of insulating materials on the cables which were not waterproof, so that the insulation in great measure depended on the ducts being kept dry.

Another conduit, which has been extensively used in America, is one composed of creosoted wood tubes, or blocks of wood of square section with a hole through them lengthwise. Several such tubes are placed to-

gether (Fig. 79) and enclosed in a creosoted wooden casing. The lengths are fitted together by turning a boss at one end of the tube, and recessing the other end, so as to make a cup for the boss to fit into as shown in Fig. 80. One great objection which has been urged against these conduits, is the destructive effect of the creosote on lead-covered cables, due to the chemi-

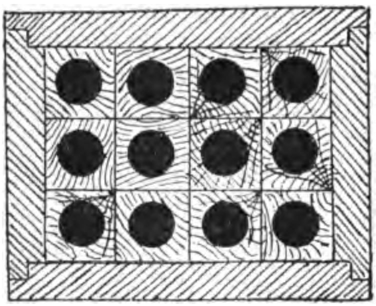

FIG. 79.

cal action which takes place between the lead and some acid which is set free from the creosote. Great trouble was experienced with cables encased in pure lead tubes, as the lead became deeply pitted with holes, and the life of the cable was very short; but with tubes of lead

FIG. 80.

alloyed with a small percentage of tin, the corrosion is very much diminished, and the life of the cable correspondingly increased.

With few exceptions the conduits for drawing-in systems in England are of iron pipe, either cast or

wrought, or of stoneware or Callender-Webber casing, the former being laid in the ground singly, and not embedded in concrete or grouped together in the American way. It appears to have been recognised that it is practically impossible to maintain any underground conduit dry, or gas-tight; and that, when this is attempted, the result is generally that, although the water and gas cannot be kept out of the conduit, the latter is well enough made to retain them when once in. For this reason, in many cases, no attempt is made to get tight joints, but provision is made to facilitate the escape of either water or gas which may have entered; and for the rest, an insulated cable whose covering is waterproof is used, and no dependence is placed on the conduit, except as a mechanical protection. Looked at from this point of view, the cast-iron socket pipe forms the most satisfactory conduit, as it affords the most perfect protection from mechanical injury, is very durable, occupies but little space, and is well adapted for use when obstacles are met with, as the alignment can easily be altered, more especially when the rubber ring joint is used instead of the lead joint.

A very important item in any system of conduits is the manholes, which should be placed at all corners, and at intervals of 60 to 100 yards in straight runs, according to the size of the cables. Where a number of cables are run together, or at places where branches are taken off in several directions, a brick manhole (Fig. 81) may be used, fitted with a cast-iron frame at the top, in which is seated the cover; this latter being also a cast-iron frame, filled in with material which corresponds with the surrounding pavement. A form of manhole or surface box very often used is a rectangular cast-iron box (Fig. 82), with a cover as

described above, and with outlets cast on it corresponding to the number and positions of the pipes to

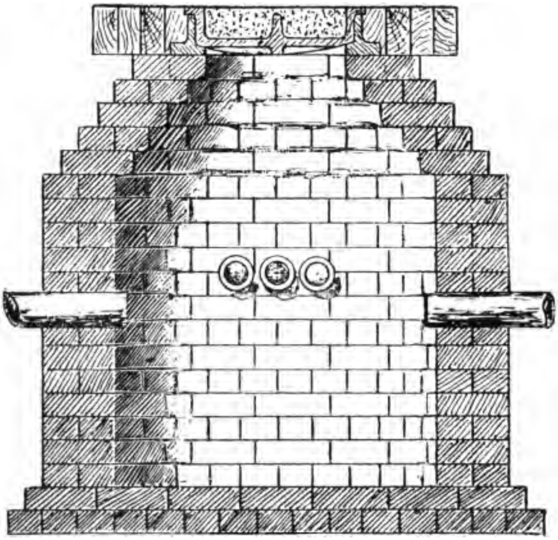

FIG. 81.

which it is to be connected. These boxes are often made without a bottom, or with a perforated bottom; and are set on rubble to facilitate the draining away

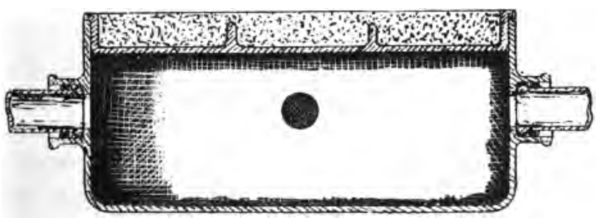

FIG. 82.

of water which may collect in them from the pipes, which latter, wherever possible, are laid with a slight

dip towards the manholes. For convenience of access to the cables these boxes should be made as large as possible; but, as already mentioned, there is an objection to this as increasing the risk of accumulation of gas; and if a large box is provided, its cubic capacity should be reduced as much as possible by filling it with blocks of incombustible material which can be removed when any work has to be done in the box. For the same reason the ends of the pipes should be plugged, and it is preferable to use a box

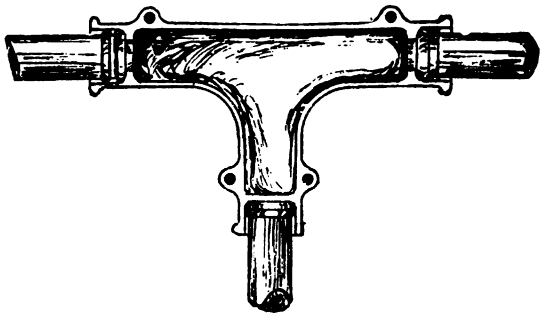

FIG. 83.

of which the walls and bottom can be made impervious to gas. In addition to these larger boxes, which are required for drawing the cable in or out, and in which the more important branches are jointed to the main cables, service boxes are required for house connections; and these may be similar boxes of smaller size, or split pipes (Fig. 83), and should be placed opposite every alternate party wall. In some low-pressure systems the joints between the various lengths of cable, and between main and branch cables, are not soldered and covered with insulating material, but are made by clamping the conductors together; and when this is done special boxes are pro-

vided, either filled with oil or other insulating compound, like the joint boxes described and illustrated in Chapter X., or arranged with watertight lids and inlets, so as to exclude moisture as much as possible. Several types of surface and joint boxes, as used by the various Supply Companies, are described in Chapter XVI., in which particulars are given of the systems employed by many of them.

As the conduit is laid underground, a wire should be threaded through each duct, and left, with its ends made fast in the surface boxes, ready to be used for drawing in a hauling line; and the ducts themselves should be examined to see that the insides are smooth, and that the ways are not blocked, as any obstruction left in them may be the cause of much trouble when the cables are being drawn in. A good plan is to draw a length of chain through the pipes before introducing the cable, as this cleans out the way or indicates the existence of an obstruction. If any obstruction is left in, or if a wire is broken in the conduit, rodding must be resorted to to clear away the block, or to thread a fresh wire through. For this, cane rods 3 to 4 feet long, and provided with screw ferrules at their ends, may be used, the rods being passed into the duct and jointed together as they go in.

For drawing in the cables, the drums on which they are coiled are mounted on stands, so that they are free to revolve; and these stands are fixed in any convenient position near the surface box, at which the cables are to enter the conduit. The end of the cable is attached by a strong but smooth fastening to a rope, and this rope is first pulled through the duct by means of the wire which had been left in it, and is then used to draw the cable through. In straight runs the length of cable that can be pulled through at

one time depends on its weight, but in street work it is very seldom that this limit can be reached, owing to the frequent changes of direction of the conduit; and when the cable has been pulled through as far as it is thought advisable, or when there is any sharp bend in the conduit, it must be brought to the surface and laid on the ground in long flakes. When sufficient cable to reach to the end of the run has been pulled through, the hauling rope is drawn through the next length of conduit, and the cable is pulled through in a similar manner.

When a long length of cable is being drawn in, the friction between it and the surface of the duct may be considerable; but this may be much reduced by lubricating it with blacklead or whiting; and when this is done, and care has been taken to see that the surface of the duct is smooth, and that there are no obstructions left in it, the cables can be pulled in without fear of damage.

With heavy cables, such as are required for low-pressure circuits, it is best to provide a separate way for each; but with the smaller cables generally used on high-pressure circuits, two may be drawn into the same duct, in which case they are both attached to the same hauling rope and drawn in together.

With regard to the general arrangement of the system of underground mains, means should be provided for disconnecting sections of them for testing purposes, or for making fresh service connections or repairs, without stopping the supply of current to the consumers; and it is therefore advisable, wherever possible, to loop the mains, so as to give two separate routes from the generating station to any point in them, and to arrange that they can be easily divided

up into comparatively short sections. This subdivision of the mains is easily arranged on low-pressure circuits, where there is very little objection to bare clamped joints, if made in a suitable box underground; but the greater difficulty of preventing serious surface leakage, and the objections to the conductor being exposed, when high pressures are used, are strong arguments against any similar arrangement, and in favour of all parts of the high-pressure circuit which are underground being covered with a continuous coat of insulating material, unless special precautions are taken to keep the boxes perfectly dry, and to enable the cables to be disconnected without any danger of contact with the conductors.

CHAPTER XV

Safety Devices.—Cardew's Earthing Device.—Drake and Gorham's Earthing Device.—Acheson's Discharger.—Earthed Circuits.—Three-wire System with Earthed Middle Wire —Concentric Cables with Earthed Outer Conductor.— Earthing to prevent Interference with Telephone Circuits.

Before passing on to the description of the underground mains actually in use in some of the more important supply undertakings, it will be convenient to mention one or two points connected with the general arrangement of the system of distribution, such as the use of safety devices to prevent the introduction of high pressures into house circuits, and the use of earthed conductors.

In the ordinary direct two- or three-wire system, in which the pressure does not exceed 200 to 250 volts, there is practically no danger to be apprehended from a personal contact with the conductors; and, in the opinion of many engineers, the same may be said of circuits using pressures up to 400 or 500 volts; but there is no doubt that pressures such as are used in the primary circuits of transformer systems are dangerous, and it is therefore necessary to take special measures to prevent their introduction into a house-circuit when, from some accident, the primary and secondary conductors get in contact. The desired protection can be attained if the difference of potential between any part of the secondary circuit and earth is not allowed to exceed a definite fixed value, such as 300 or 400 volts, and an apparatus has been designed by Major Cardew to effect this object by automatically

connecting to the earth any conductor as soon as its potential differs from that of the earth by the fixed amount for which the apparatus has been adjusted.

This apparatus consists of two brass plates insulated from one another by ebonite rings and collars, and bolted together. Between them is placed a thin aluminium foil attached at one end to, and lying on, the lower plate; when the difference of potential between

FIG. 84.

the two plates reaches a pre-determined amount, the static attraction lifts the free end of the foil, and electrically connects the two brass plates. The plates and discs are fitted together and adjusted in the factory, and are pushed in between two sets of springs, fixed to a block of ebonite. The upper spring is connected to the house wire, and the lower spring to earth, and the foil therefore, when it connects the two brass plates, earths the house wire, and thereby prevents a dangerous difference of potential from being

maintained between any part of the secondary circuit and the earth. In practice this causes a sufficient increase of the primary current to blow the main fuse, and cut off the installation from the supply mains.

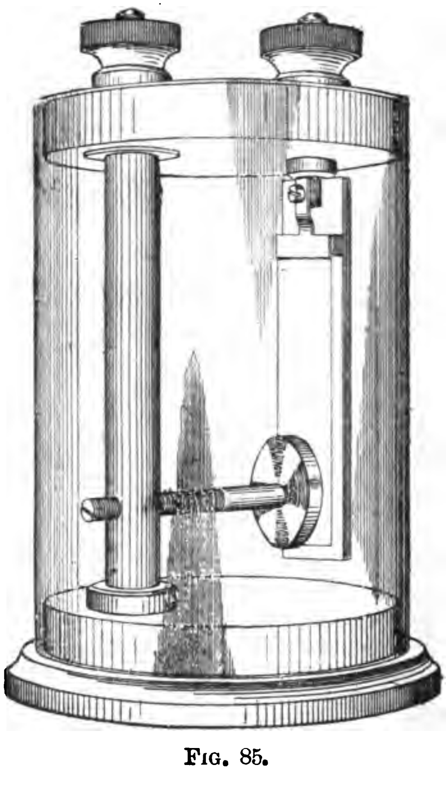

FIG. 85.

The apparatus, a general view of which is given in Fig. 84, is enclosed in a strong cast-iron box, and is fixed in any convenient position near the main switch-board.

Another earthing device on the same principle, which has been constructed by Messrs. Drake and Gorham, consists of a glass cylinder, closed at either end by an ebonite base and cap. A stout brass rod runs from top to bottom (Fig. 85), and to this is fitted an adjustable rod with a flat disc at its end, this rod being connected to the house wires. To a second terminal, which is connected to earth, is attached a brass plate, from the upper end of which is hung an aluminium foil, in such a manner that its free end is opposite the brass disc, and can be attracted to it, when there is a sufficient difference of potential between the house wire and the earth.

Another safety device, designed however in this case to protect the cable, may be mentioned here, as it does not appear to have received much attention in England, although largely used in America. The advantages of using an apparatus to prevent the breaking down of the insulation of an arc light circuit by a static discharge were first pointed out by Mr. Acheson in a paper read at the 1888 Convention of the National Electric Light Association at New York; and the remedy proposed by him was to connect one terminal of a lightning protector to the conductor, and the other to the sheathing of the cable or to earth, so as to provide for each section of the circuit an easier discharge path than that offered by the dielectric of the cable.

Reverting again to methods for preventing the introduction of high pressures into house-circuits, we have already mentioned the plan of interposing a metallic shield connected to earth between the primary and secondary circuits of the transformer, so that no contact can take place between these two sets of conductors without at the same time connecting them to

earth, as also the method of permanently earthing one conductor of the secondary circuit. The former of these plans often introduces constructional difficulties, and the latter is not so good as that in which automatic earthing devices are employed, as it may fail if the secondary winding of the transformer is broken.

Another case in which the earthing of one of the conductors has been proposed as a means of preventing the introduction of too high a pressure into the house-circuit is that of the three-wire direct system, when a pressure of 400 to 500 volts between the outer conductors is used. In such a system, if all the conductors are insulated, a fault on one outside conductor may give rise to a difference of potential between the other outside conductor and earth which is equal, or nearly equal, to the full working pressure; whereas, if the middle conductor is earthed, it is impossible for the difference of potential between either outer conductor and earth to exceed half that amount. As the earthing of any conductor in a house-circuit in the direct system affects the corresponding conductor throughout the network, we propose to briefly consider how such an earth connection will affect the working of the system and its maintenance in good working order.

The effect of permanently earthing the middle conductor is that all leakage circuits to earth from either of the outer conductors become more or less complete short circuits between these latter and the middle conductor, so that it is no longer possible to measure the insulation resistance of either outer conductor from earth, as this resistance is always in parallel with that of the lamp circuits, and cannot be separated from it. It is held by some of the advocates of earthed systems that this is no real disadvantage, as they

argue that in an extended system of mains, even when all the conductors are insulated, it is impossible to detect and localize faults by the usual methods of testing the insulation resistance of the cable from earth; whereas with an earthed middle wire, since every fault is of the nature of a short circuit, it will automatically remove itself from the circuit by blowing a fuse, and will indicate its locality by cutting off the current from a portion of the circuit. This method of maintaining a system of mains in good order certainly has the merit of simplicity; but it cannot be considered satisfactory, as the fault will not be localized by the blowing of the fuse until the leakage current has assumed very considerable proportions, and then only at the expense of great inconvenience to the consumers.

This will be easily understood, if we consider the conditions that will exist in practice. The system of mains must be divided into sections protected at each end by fuses placed in surface boxes, and in each of these sections the current delivered to the consumers will vary very considerably at different hours of the day and at different seasons of the year. The fuses must be so proportioned that they will not blow except with a current at least 25 per cent. greater than that required for the maximum number of lamps that may be lighted, as otherwise they may blow, as is often the way of fuses, when there is no fault on the mains. The normal maximum current will probably not exceed two-thirds of the occasional maximum, and for many hours each day the current may be only a small fraction of the maximum; so that it may happen that a fault may exist for many days without blowing the fuse, unless the leakage current is nearly equal in value to the normal maximum current re-

quired for the consumers in the section. Now faults do not always develop very rapidly, and if no tests are made, and the mains are left to take care of themselves until a fuse blows, it is probable that a number of faults will exist in the circuits, each too small to allow sufficient leakage current to pass to blow a fuse, but giving in the aggregate a considerable leakage current, and each presenting a weak spot in the system; since, if the resistance of any of these faults decreases, or the demand for current in the section increases beyond the normal, the fuse may blow and cut the current off the section. This will happen, not during the daytime when the inconvenience would be least; but at the time of maximum demand, when the consumers will be most inconvenienced by the extinction of their lamps, and when the repairs which will be necessary before the section is again ready for service will be most difficult to execute.

If a fault occurs in a house-circuit, the conditions are very much the same, as the leakage current may have to attain a considerable value before the fuse blows; and even then it is not certain that the fault would be removed from the circuit, as in many cases the fuse would be at once replaced by another one, and, if necessary, by one that would carry a larger current.

If, on the other hand, all the conductors are insulated, it is possible to keep a continuous check on the insulation resistance of the mains by the use of recording instruments fixed in the central station; and when these instruments indicate any important change in the condition of the mains, tests may at once be made to localize the newly developed fault. By these means the system of mains may be kept in good working order, and faults can generally be re-

moved before they have become sufficiently serious to interfere with the working; and, in the author's opinion, it is far better to adopt this plan, however long and tedious the localizing of faults by testing may be, rather than risk having a system of mains in which a number of faults may continue to exist until the leakage current becomes sufficient to blow a fuse, and in which so much inconvenience is likely to be caused to consumers by the extinction of their lights at the time of maximum demand.

In the case we have just been discussing we have supposed the middle wire permanently earthed all along, or at frequent intervals along its length; but there is another plan which may be adopted, in which the middle wire is earthed only at the station, so that, when necessary, the earth connection can easily be broken, or be increased in resistance. If this earth connection is made through a low-resistance ammeter, the readings of this instrument will give a fair indication of any changes in the condition of the mains, and their fault-resistance can be determined by momentarily increasing the resistance of the earth connection (see Chapter XVII.); and further, this connection can be altogether broken if necessary for making other tests. At the same time, except whilst tests are being made, this plan retains the advantages of restricting the difference of potential between either outer conductor and the earth to half the working pressure.

When concentric cables are used with the outer conductor earthed, the same objection does not hold good; as, in any case, the condition of the concentric cables cannot be determined by measuring the fault-resistance to earth of the conductors. This difficulty of testing concentric distributing mains is a great

objection to their use; but in alternating current systems, as was explained in Chapter VIII., they have important advantages which may more than counterbalance the increased difficulty of testing. In direct current systems, however, no such advantages exist, so that the use of separate cables is much to be preferred on account of the greater facilities for testing and jointing.

The use of a permanently earthed middle wire has also been recommended as a means of preventing interference with telephone circuits using an earth return, and this claim has been investigated by the Verband Deutscher Elektrotechniker in connection with a dispute between the German Post Office and the Town Council of Altenburg, who proposed to use a bare middle wire. The report of the Verband was published in 1895, and was favourable to the use of the earthed middle wire; but the author cannot agree with their conclusions, as, so far as he has been able to learn, no trouble has been experienced in any installations in England using three insulated conductors. The report states that with three insulated conductors the negative has the lowest insulation resistance, and the leaks generally occur in the houses; and that, if a fault occurs in one of the other conductors, there is a leakage current from this fault to all the weak points in the negative, some of which may be at a considerable distance away, so that currents sufficient to affect the telephones may pass from point to point through the earth. When an earthed middle wire is used, it is claimed that the leakage currents pass from the faults direct to the nearest point of the middle wire, and further, that the faults are immediately removed by the fusing of the cutouts.

The first part of this statement may be true, if faults are allowed to develop until the leakage current becomes large enough to blow a fuse; but such a condition of affairs should not exist if systematic testing is carried out, and faults are removed as soon as they are detected; and with the usual conditions, in which the only leakage is that due to a large number of high resistance faults mostly in the house-circuits, there is practically no danger of interference with the telephone circuits. On the other hand, the earthing of the middle wire may cause earth currents due to the difference of potential between different points of the middle wire itself. This point is dealt with in the report, but the mistake is made of supposing that, because the difference between the currents leaving the generating station by the two outer conductors is only, say, 10 per cent., therefore the current in the middle wire in any part of the network is only 10 per cent. of that in the outer wires. This is a conclusion that is certainly not warranted, as it is well known that the distribution of the load in individual sections will vary much more than this, and the author would rather put this figure at 25 per cent. than at 10 per cent. If then we suppose two distributors starting from a feeding point, in one of which the load on the positive side is 25 per cent. greater, and in the other 25 per cent. less than that on the negative side, we may get a very considerable difference of potential between two points on the respective middle wires; indeed, it may be equal to the maximum difference of potential allowed between any two points of an outer conductor, or say 8 or 10 volts on a 400 volt circuit. It is undoubtedly possible that interference may take place either with an earthed or an insulated middle wire; and, in the author's opinion, there is very little

to choose between the two; and certainly there is no such advantage to be gained by earthing the middle wire as will counterbalance the disadvantages pointed out in the earlier part of this chapter.

CHAPTER XVI

Underground Mains of the Westminster Company.—Crompton Culvert.—Kennedy Culvert.—Insulated Cables.—Kensington and Knightsbridge Company.—St. James' and Pall Mall Company.—Chelsea Supply Company.—Charing Cross and Strand Supply Company. — Bradford. — Brighton. — Edinburgh.— Glasgow.— Liverpool.—Manchester.—Berlin. — Paris. — Brussels.—America.—London Electric Supply Company. — Metropolitan Electric Supply Company. — House-to-House Electric Light Company.—City of London Electric Lighting Company.—County of London and Brush Provincial Company.—Islington Vestry.—Bristol.—Leeds. — Newcastle. — Portsmouth.—Continental High-pressure Circuits.—American High-pressure Circuits.

Although in 1888 very few electricity supply stations were at work, a large number of central electric lighting stations have now been put into operation; and in connection with one or other of these stations most of the systems of underground mains that have been described have been put to the test of practical working. It is proposed, therefore, to describe the particular methods employed in some of these installations, first taking those which employ low-pressure direct currents, and then those using high-pressure currents with transformers.

The distribution of low-pressure currents is in all cases effected by means of underground mains, as the weight of the cables required for the heavy currents would make the erection of overhead lines both difficult and costly; and further, various methods can be employed with a view to lessening the cost of these underground mains, which would not be permissible where high pressures are used. The most prominent example of these is that in which bare copper strip

supported on insulators is laid in a culvert; and of this system there are several types in use.

THE WESTMINSTER ELECTRIC SUPPLY CORPORATION.

The underground mains of this Company may be taken first, as in their network will be found examples of each of the three most important methods which are now employed, viz.:—bare copper strip, continuously insulated conductors drawn into conduits, and continuously insulated conductors built in. The current is distributed on the three-wire system, with 200 volts between the outer conductors, from the generating stations and from distributing centres, at which are placed batteries of accumulators, which are connected to the generating machinery by two-wire feeding mains. Wherever it has been possible to find sufficient space for the culverts required for the bare wire system, this method of laying the conductors has been employed; and when space has not been available, continuously insulated cables have been laid, either on a drawing-in or a built-in system.

Two bare wire systems are in use, the mains which were first put underground being laid in culverts on the system introduced by Messrs. Crompton & Co.; whilst those of later date have been laid on a system devised by Prof. Kennedy, the Engineer of the Company. The Crompton culvert consists of a concrete trench built under the footway, in which, at intervals of from 10 to 20 yards, are set glass insulators on which the copper strips are carried. Figs. 86 and 87 show respectively a cross-section and a longitudinal section of an ordinary three-wire culvert, the inside dimensions of which are 15 inches wide by 12 inches deep, whilst the outside dimensions are about 29 inches by 21 inches. The insulators are carried on stout oak crossbars (which are built into the concrete

so as to leave a clear space of a couple of inches or so between their under sides and the floor of the culvert); and they are made with a number of corrugations on their outer surface, so as to increase the resistance to leakage; and with a deep notch on the top which forms a recess in which the conductors rest. The conductors consist of one or more strips of copper, 1 inch wide by ¼ inch thick, according to the current to be carried, and are laid flatways in the recess in the

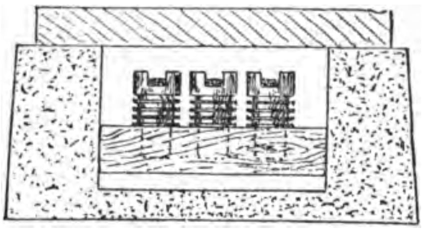

FIG. 86.

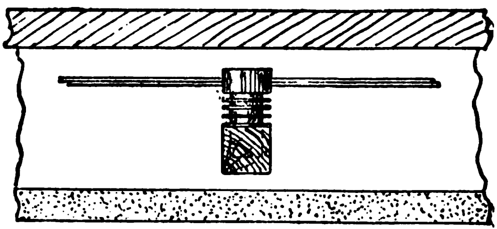

FIG. 87.

insulators. As the distance between the insulators is considerable, the tendency of the copper strips to sag down between the supports has to be counteracted by straining the strips; and therefore, straining boxes are placed at intervals depending on the length in which the strips can be delivered, or on the length of the culvert which can be built in a straight run. At these boxes two oak bars,* of a larger cross-section,

* At Westminster, these oak bars have now been replaced by iron bridges of much stronger construction.

are built in across the end of the culvert, and to them are fixed insulators placed horizontally, as shown in Figs. 88 and 89; one insulator being provided on each crossbar for each line of conductor. Each of these pairs of insulators supports a gun-metal bridge, having a rectangular hole through which the conductor passes, and in which it can be securely clamped by means of two set-screws.

The method of laying a section of main is to pass

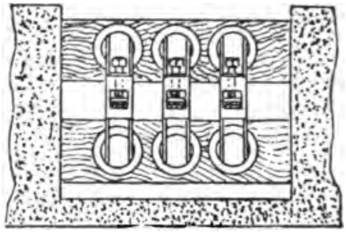

FIG. 88.

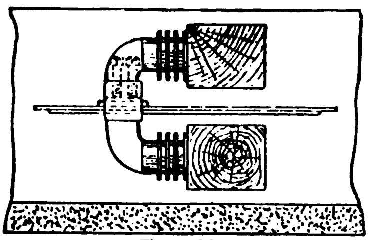

FIG. 89.

the copper strips into the culvert, place them in the notches in the insulators, and pass them through the holes in the gun-metal bridges. One end is then made fast by tightening up the set-screws in the bridge, and a tensile strain is put on the other end by means of a screw-tightening gear; and, when the strip is sufficiently strained, the set-screws in the bridge are tightened up, thus holding it securely in place. The culvert is covered by flagstones, and over the top of

these stones the ordinary paving is relaid. At each set of insulators a manhole cover is provided, so as to give access to them; and these manholes are used as service boxes, from which the house connections are taken. Similar culverts, but of greater width, are used for accommodating a three-wire distributing main and a two-wire feeding main, or two three-wire mains may be laid side by side; the arrangement of insulators, etc., being the same in each case except as regards the number fixed on each crossbar.

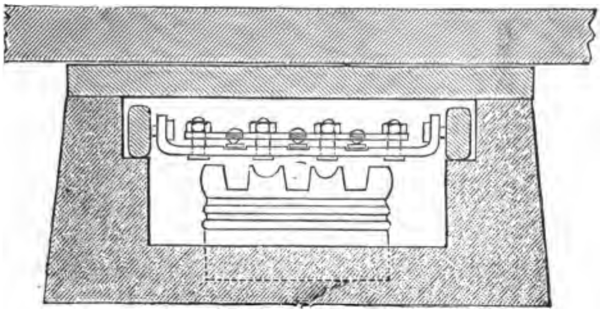

FIG. 90.

The Kennedy culvert system differs from the one just described, in that it has been specially designed with a view to facilitate the drawing in of the conductors after the culvert is completed and covered in, and that the straining gear has been rendered unnecessary by placing the insulators at much shorter intervals. This arrangement simplifies the operation of laying the mains very considerably; but it has of course the disadvantage that, owing to the larger number of insulators, there must be a correspondingly greater chance of surface leakage, and this disadvantage is greater in cases where higher pressures, such as 400 to 500 volts, are used. The culvert is built of concrete, and two sizes are generally employed, one to carry a three-wire distributing main (Fig. 90), being 15 inches

wide by 7½ inches deep, inside measurement; and the other (Fig. 91) to carry a three-wire distributing and a two-wire feeding main, being 20 inches wide and the same depth. The space occupied by these culverts

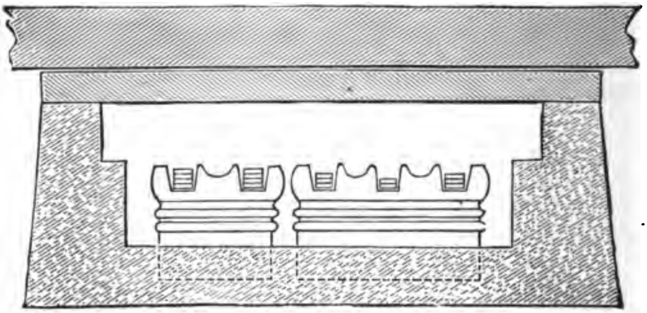

FIG. 91.

underground is 26 inches and 31 inches respectively in width by 12 inches in depth. The concrete is shaped as shown in the figures by means of templates, the culvert being wider inside at the top than at the bottom, so as to form a ledge on each side, and thus

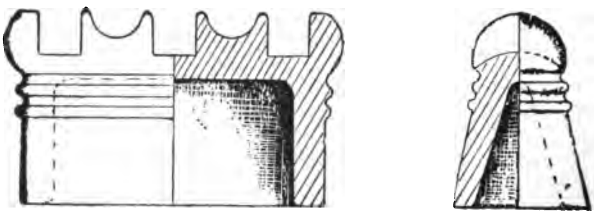

FIG. 92.

provide a pair of rails on which the drawing-in trolley can run.

At intervals of 6 feet, hollow stoneware insulators (Fig. 92) are embedded in the concrete floor of the culvert, these insulators being moulded with several

corrugations to increase the length over which surface leakage must take place, and with deep slots in which the copper strips can lie. The drawing-in trolley, shown in position in Fig. 90, consists of a bent iron plate supported on four teak wheels, which run on the ledges provided on the sides of the culvert; in this plate notches are made corresponding in position to the slots in the insulators, and in these notches the

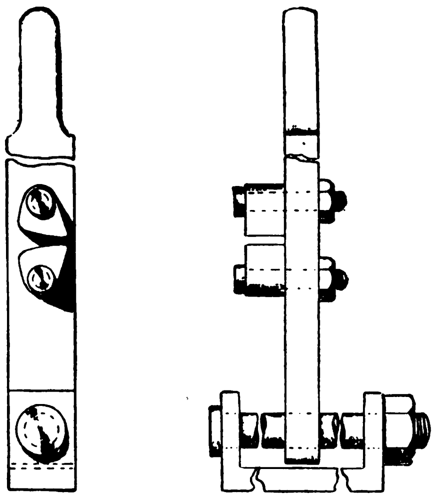

FIG. 93.

copper strips are laid. A cover plate is provided in which are fixed pointed steel set-screws, which can be jammed down on the copper strips by bolts which pass through both plates.

When a conductor is to be drawn into a completed culvert, it is first laid out on the pavement, and straightened by means of a special tool (Fig. 93), which consists of a lever, turning on a bolt in a frame which can be fixed to the ground; to this lever are

attached two cams with milled edges, which are free to turn on studs screwed into the lever; between these cams the copper strip is held tightly, and a considerable strain is put on the strip by pulling the lever over. The strip is then clamped in position between the plates of the trolley, so that it will be led fairly over the slots in the insulators in which it is to lie; and the trolley is hauled through the culvert by means of a rope previously drawn through. This method of drawing in the conductors has been found very convenient, as it does away with the necessity for the numerous surface boxes required in other systems, and thus renders it possible to place the culvert under the

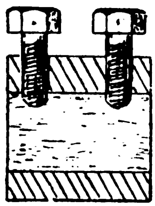

Fig. 94.

roadway, when this is a more convenient position than under the footway.

The copper strips are 1 inch by $\frac{1}{4}$ inch, and can be obtained in lengths of about 50 to 60 yards; the various lengths of strip are joined at the manholes by tinning the ends and clamping them together in a metal connector (Fig. 94).

Owing to the large amount of space occupied by these concrete culverts, it is frequently impossible to find room for them, and when this is the case continuously insulated cables are employed. In some few cases, lead-covered and armoured jute cables, laid in the ground with a board placed over them to give

warning of their presence, have been used for feeders; but, with these exceptions, the cables used by the Westminster Company are insulated with vulcanized indiarubber, and are drawn either into bitumen casing or into iron pipes. The connection between a cable and the copper strip (Fig. 95) is made by sweating on to the conductor of the cable a lug having a projecting tongue, and clamping this tongue and the copper strip together, in a connector like that shown in Fig. 94.

Wherever possible, the distributing mains are under the footway, and service boxes are placed opposite

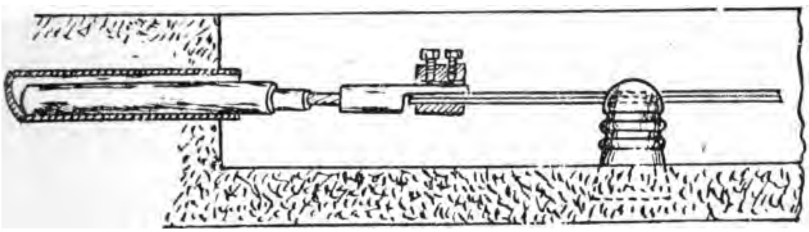

FIG. 95.

every other party wall; the house connections being made with vulcanized rubber cables laid in iron pipes.

The Crompton system was first used by the Kensington and Knightsbridge Electric Lighting Company, who employ a three-wire low-pressure system of distribution with accumulators, and it has also been laid down by Messrs. Crompton for the Notting Hill Electric Lighting Company, and in many provincial towns; in all cases, however, it has to be supplemented by insulated cables, owing to the difficulty of finding room under the footway for the culvert. In most cases the cables used are insulated with vulcanized rubber, and drawn into iron pipes; though other cables, such as the bitite cables, have also been laid.

THE ST. JAMES' AND PALL MALL ELECTRIC LIGHT COMPANY.

This company distributes electricity at low pressure on a three-wire system from two generating stations: one at Carnaby Street, and the other at Mason's Yard; but the latter only runs during the hours of maximum demand in winter, the greater part of the energy supplied being generated at the Carnaby Street station, which runs continuously throughout the year. Although the distributing mains are connected together throughout the whole area to form one network, this area is, for feeding purposes, divided into three districts, each of which is supplied by a set of feeders; one set supplying the Carnaby Street district, another the Mason's Yard district, and the third the Piccadilly district. During the hours of light load, current is supplied to the network by one set of feeders only, but as the load increases and the pressure in their districts tends to fall, the other feeders are brought into use, current being generated at Carnaby Street at three different pressures, to suit the requirements of the three sets of feeders.

The mains which were first put down when the Mason's Yard station commenced working were bare wire mains. These mains consist of strips of bare copper 2 inches by $\frac{1}{10}$th of an inch, set edgeways in slots in porcelain bridges fixed in an iron trough. One or more strips are placed in each slot according to the sectional area required, the usual sizes being 1·6, 0·8, 0·4 square inch section for the outside conductors, and half these areas for the middle conductors, thus giving a joint area of 4 square inches in the largest size, and of 2 square inches and 1 square inch respectively for the two smaller sizes. The cast-iron

troughs, a longitudinal and a cross section of which are shown in Figs. 96 and 97, are made in lengths of 3 or 6 feet, and are jointed by trough-shaped pieces, about 6 inches long, which enclose the iron trough, the joint being made water-tight by running in lead. The troughs are laid wherever possible with a slight

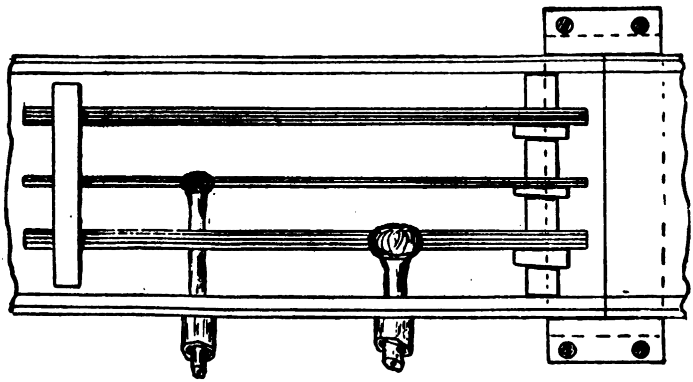

FIG. 96.

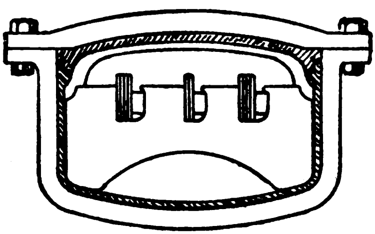

FIG. 97.

fall towards the junction boxes, and the porcelain bridges are so shaped as to allow a free passage to any water which may get into the trough. The junction boxes are connected to the drains, and when a dip occurs which cannot be drained direct, arrangements are made to siphon out the water. Between the

porcelain bridges on which the copper strips rest, are placed porcelain saddles, which hold the strips in place, and prevent any chance of contact between them. The trough is closed by a cast-iron cover, which rests on a ledge cast on each side in the trough, and the joint between them is made tight with red-lead and yarn. Junction boxes of brick are provided about every 100 feet or so, and in these provision is made for disconnecting the mains, for testing and other purposes. In addition to the bare wire mains described above, there are now in use lead-sheathed and armoured cables laid direct in the ground, and insulated cables drawn into conduits; the former being used chiefly for feeders, and the latter for distributors. The conduits used are of bitumen concrete, stoneware or cast iron; and in them are laid cables insulated with bitumen or vulcanized india-rubber, or with paper or fibre protected by lead sheathing. Brick boxes are provided for making connections between the sections of main and for house services, the services being made with insulated cables laid in pipes; and in all these boxes special precautions are taken to prevent damp getting to the conductors by entirely covering the joints with waterproof compound put on hot.

THE CHELSEA ELECTRICITY SUPPLY COMPANY.

The system employed by this company is a continuous current transformer system with accumulators, current being transmitted at high pressure from the generating station to several sub-stations situated at various points in the district, and thence distributed at low pressure to the consumers. In the system as first laid down, the accumulators at the sub-stations were charged in series and discharged in

parallel, as in the system described on page 80; but now the batteries are always connected to the distributing network, and are charged from the low tension side of continuous current transformers, the primary circuits of which are supplied with current at a pressure of 1,000 volts. The secondary circuits of the transformers can also be connected to the distributing network, so that at times of maximum load the batteries and transformers can supply current in parallel to the mains. The charging takes place during the hours at which the output from the substations is not at its maximum, and when the demand is very small the generating plant can be stopped and all current supplied by the batteries; so that it is possible to avoid working any generating unit except at full load.

The secondary distribution is effected on the three-wire system, the distributing mains throughout the district being connected together to form one network, fed by feeders from each sub-station. The cables are insulated with vulcanized bitumen, and are drawn into bitumen concrete casing or stoneware conduits, manholes and joint boxes being provided as required to facilitate the drawing in or out of the cables and the connecting of branches and house services.

The Charing Cross and Strand Electricity Supply Company.

The system of distribution used by this company is the three-wire continuous current with 200 volts between the outer conductors. The first cables, which are still in regular use, were laid in 1887 for a two-wire 100 volt system, and are bitite laid in wooden troughs filled up solid with bitumen. In 1891 the three-wire system was adopted, and Callender casings

were, laid so as to provide for future extensions, into which bitite cables have been drawn as required. For convenience in drawing in the cables, brick boxes about 2 feet square are provided, whilst smaller ones of the same type are used for service connections, which are made by clamp connectors. Where space is not available for laying casings, lead-covered and armoured jute cables are used, testing boxes of cast iron, in which the connections are made by links, being fixed in brick pits at convenient positions, and service connections being made in cast-iron boxes buried in the ground.

Current is supplied to the distributing network from two stations, the original one in the Strand district having been supplemented by a second one on the south side of the river, at which current is generated at 1,000 to 1,100 volts, and transmitted to motor generators through heavy trunk mains laid on Callender's solid system, consisting of bitite cables laid in cast-iron troughs and run in solid with bitumen.

Bradford Corporation.

The system originally adopted at Bradford was a two-wire continuous current system working at a pressure of 115 volts, but in 1896 it was found necessary, in order to meet the increased demand for current, to change to a three-wire system with 230 volts between the outer conductors, and soon afterwards the pressure of supply was again increased, so that the system at present in use is a three-wire system with 460 volts between the outer conductors. The first cables laid down were lead-covered jute cables, the feeders and some of the distributors being armoured with two steel tapes, whilst the bulk of the distributors were simply lead-covered, without further mechanical

protection. These cables were laid direct in the ground at a depth of about 2 feet and covered with boards, except at road crossings or other places where special protection was required, in which case they were run through stone channels. Extensions have been made with similar cables, the specification for them stating that they may be insulated with jute, paper, or compound, and must be enclosed in a solid tube of lead, coated with compounded jute yarn, armoured with two steel tapes and again served with compounded yarn. The original feeders had each a pilot wire laid up with it, but separate pilot wires were afterwards laid down; and at present the pilot wires are composed of three cores insulated with bitumenized fibre and laid up together and then lead-covered and armoured.

Straight joints in the cables are made by inserting the ends of the two conductors into a tinned brass tube, so that they butt up against one another, and then soldering the whole together. The joint is then enclosed in a cast-iron split box, which extends some way over the armouring on each side of the joint. When the two halves of the box have been bolted together, it is filled up through a hole in the top with an insulating compound, which when cold makes a solid watertight joint. The T joints and house service connections are not soldered, but are made with a clamp, and are then enclosed in a cast-iron box which is filled with compound.

Brighton Corporation.

The system adopted at Brighton is a continuous current three-wire low-pressure system with 230 volts between the outer conductors, supplemented for the outlying districts by a high-pressure alternating cur-

rent system, with transformers in sub-stations supplying a low-pressure three-wire network. This low-pressure network is not, however, at all times supplied with alternating current from the transformers, but only during the hours of maximum demand, that is to say, from about sunset till eleven or twelve o'clock at night. From this time till sunset the following day this outlying network is connected to the mains supplying the central districts with continuous current, so that the alternating current plant can be stopped down, and the losses avoided which would otherwise result from running the alternators and transformers on light load during about 18 hours out of the 24. The distributing network, which can be supplied by either method, is divided into sections, each of which can be connected to one or more transformer sub-stations, or at one point only to the continuous current mains. At this point is fixed an interlocking change-over switch, by means of which the section of the network can be connected either to the continuous current or alternating current supply. If the section is supplied by more than one transformer, these others are each provided with a switch, and a system of locks and keys has been arranged which prevents any one of these transformer switches being closed so long as the change-over switch connects the network to the continuous current mains; or when changing from alternating to continuous current supply, it in like manner locks the change-over switch and prevents it being switched over from the alternating to the continuous current mains until all the other transformer switches have been opened.

The cables are all insulated with fibrous material, lead-covered and armoured, and are laid direct in the ground and covered by a layer of ordinary hard bricks;

the continuous current cables being single, whilst those in the districts using alternating currents are concentric. Straight and tee-joints are made in cast-iron boxes filled with insulating compound in the manner described in chapter X.

Edinburgh Corporation.

The system of distribution employed at Edinburgh for the central part of the town is a three-wire system with 460 volts between the outer conductors. The distributing network is fed by two-wire feeders, the third wire of the distributors being brought back to the generating station from three or four points only in the network. For the outlying parts of the town a 2,000 volt alternating current system with transformers is employed, and a rectified alternating current is also used for arc lighting in the streets which are not served by the three-wire low-tension mains.

The feeders for the low-pressure system consist of bare copper strip laid in conduits on the Kennedy system, already described; or, where space was not available for the bare wire conduit, of lead-covered and armoured fibrous insulated cables laid direct in the ground, and covered with tarred boards to protect them from injury from workmen's picks. The distributing cables are insulated with vulcanized india-rubber heavily braided, and are drawn into stoneware casings under the footways and into iron pipes under the road crossings. Brick junction boxes are provided at all crossings, and at intermediate points where necessary for drawing in the cable; and in these boxes the connections between the cables are made by sweating a cone connector to the end of each, and fitting these connectors into gun-metal connecting blocks. For convenience in making extensions or

alterations, the cones of all connectors are made of the same size and interchangeable, and the connecting blocks are made in series having two, three, four or five holes for taking these numbers of connectors. The cone connector terminates in a threaded shank for taking a nut, and when the cones have been entered from underneath in the holes in the blocks, and have been fixed in position by tightening the nuts, a stoneware cap is fitted over each block, so as to protect it from wet, which may drip from the box covers, and to prevent all chance of short circuit between connections at different potentials. The service connections are made with vulcanized rubber joints in small brick boxes, or, where space is limited, in special lengths of stoneware casing. These lengths of stoneware are made so that they can easily be split longitudinally, and the upper and lower halves removed, leaving the cable exposed. The upper half of the casing is replaced by a length provided with an outlet for taking the pipe containing the service wire, and when the service wires have been teed on, the two halves of the casing are replaced in position and jointed with bitumen cement.

The high-pressure cables are mostly concentric; but in some cases twin cables are now being used instead of concentrics on the rectified current arc lighting circuits. These cables are insulated with paper and lead-covered, or with vulcanized india-rubber, and are pulled into stoneware casings under the footway, and into cast-iron pipes under the roadways.

Glasgow Corporation.

The system of distribution adopted at Glasgow is a continuous current three-wire system with 200 volts between the outer conductors, but for extensions now

in progress the pressure has been increased to 500 volts. The original system of mains was largely composed of bare copper on insulators in cast-iron culverts, as shown in plan in Fig. 98 and in section in Fig. 99, but owing to the fact that this type of culvert does not fulfil the Board of Trade requirements of

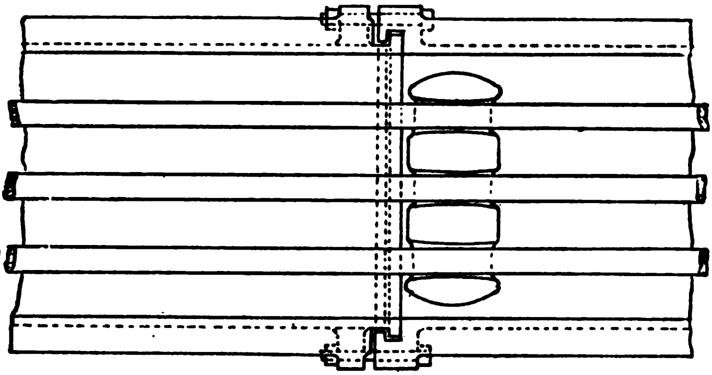

FIG. 98.

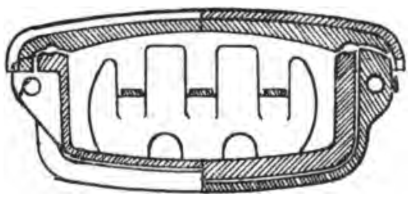

FIG. 99.

allowing easy inspection of all insulators, and also that there has been some trouble through contact of the copper strips with the iron culvert, all extensions have been made with cable. The cables used have either been insulated with india-rubber, and drawn into iron pipe, or insulated with fibrous material lead-covered and armoured, and laid direct in the ground, the latter type of cable being most often used.

Liverpool Corporation.

The Liverpool Corporation work at low pressure on the two-wire and three-wire systems from four generating stations, and use bitite cables laid on a built-in system. The cables are laid in cast-iron troughs with socket joints, into which there is first run a layer of molten bitumen, which covers the bottom of the trough to a depth of about ¼ inch. Before this bitumen sets, wooden bridges are placed in it about 18 inches apart, and on these bridges the cables are supported. Bitumen is run into the trough so as to cover the cables and fill it nearly to the top, and a cast-iron cover is then fitted on ; or sometimes a layer of cement concrete is used to finish with, in which case the iron cover is not needed. The connections between the feeding and distributing mains are made in cast-iron boxes, fitted with socket pieces to receive the ends of the cast-iron troughs ; the box is laid below the level of the pavement, so that it has a cover independent of the surface plate, which is flush with the pavement. The box cover fits into a groove cast round the joint box, and the boxes are filled in with heavy rosin oil. The connections are made inside this box by sweating copper lugs on to the ends of the cable, and bolting them to copper connecting bars, which in some cases have terminals fitted to them so that a fusible cut-out can be inserted in the branch.

Manchester Corporation.

The system of distribution employed at Manchester is a five-wire system with 400 volts between the outer conductors ; but five distributing cables are not laid in all streets, a considerable length of three-wire main being in use, and also smaller lengths of four-and two-

wire mains. The net work is fedat various points by two-wire feeders, and some of the five-wire mains are brought into the station. The balancing was originally effected by means of 100 volt generators connected up between adjacent cables of the five-wire mains brought into the station; but these generators are no longer used, and the balancing is effected partly by accumulators and partly by motor generators fixed in substations at various parts of the town (*vide* p. 75). There are at present four balancing sub-stations, each of which is an underground chamber formed beneath the footpath. The chambers are well lighted, and are kept dry and well ventilated by means of small electric blowers, which blow air into them from outside.

The cables of the same potential are all interconnected throughout the network, but provision is made in a number of junction boxes for disconnecting any section of the mains, and separating it from the rest of the network. For this purpose a vertical cast-iron pillar with tripod foot supported by three insulators is fixed in the box, and on this pillar are fixed a number of cast-iron discs one above the other, each of which carries a ring-shaped porcelain insulator, which in turn carries a gun-metal ring fitted with a number of projecting studs. The cable ends are sweated into lugs, and each lug is threaded over one of the studs, and a good connection made by clamping it up tight with a nut. The number of cast-iron discs and insulated gun-metal rings may be varied according as the pillar distributor is required for connecting mains of two, three, four or five wires, each gun-metal disc having connected to it all the cables at the same potential which enter the junction box. The pillar is hollow, and a large funnel is slipped into it at the top, which collects any water which might otherwise drip on to the connections, and

delivers it through the hollow pillar on to the floor of the box.

The conductors are insulated and protected in various ways, bare copper strip, cables drawn into pipes and built-in cables all being in use in different parts of the network. The bare copper mains originally laid down were carried in concrete culverts, bridged at intervals of six feet by porcelain insulators, the ends of which were built into the concrete sides of the culvert. The upper surface of each insulator had five slots prepared in it, in which the copper strip was placed on edge and fixed by wooden wedges. Other insulators, somewhat shorter than the width of the culvert, and having slots in their under side, were placed over the copper strip half way between the main insulators, to prevent the strips from touching one another. Owing to the large number of insulators and consequent surface leakage, this original system has not been used for extensions, which, when bare wire mains have been used, have been laid on the Crompton system, described on page 292. Service connections to the bare wire mains are made with insulated cable, the end of which is sweated into a gun-metal lug. This lug is placed on the top of the strip, and a gun-metal plate is placed underneath it, the lug and plate being clamped together by phosphor bronze bolts, so as to grip the strip and make good contact.

The insulated cables laid in the earlier years of the undertaking were insulated with vulcanized india-rubber, and drawn into cast-iron pipes, several cables being drawn into one pipe. This drawing-in system has now been abandoned for extensions in favour of Callender's solid system, in which troughs formed of pitch pine, coated with Stockholm tar, and fitted with wooden bridges at intervals of about 18 inches, are laid

in the trench. The upper surface of the bridge is grooved to receive the cables, and when these latter have been placed in position, the trough is filled up with bitumen and covered with a wooden cover, over which is laid a layer of concrete about 2 inches thick under the pavement, and from 6 to 8 inches thick under the roadway. Services are made by breaking away the concrete, sawing through and removing the cover and sides of the wooden trough for a length of about 18 inches, and breaking away the bitumen so as to free the cables. A soldered tee-joint is then made and insulated with bitite and waterproof tape. The sides of the wood trough are then replaced, and a similar but smaller trough, with the bottom cut away where it crosses the main trough, is laid for the service cable in such a way that its sides rest on the sides of the main trough and pass completely across it. The service trough and that part of the main trough, where the bitumen has been broken away, are then filled up with bitumen, the wood cover is fitted on, and the service trough is further protected by channel-shaped cast-iron covers laid over it so as to protect the top and sides.

The service wires are insulated with vulcanized india-rubber, and at first were laid in iron pipes; but as this method was not found satisfactory, rubber cables armoured with steel tapes and drawn into an earthenware pipe were tried; and finally the system now exclusively used was adopted, which consists in laying armoured rubber cables in wooden troughing, filled up with bitumen in the manner described above.

Continental and American Systems.

The largest low-pressure system on the Continent is that at Berlin, where current is supplied from several

stations to a network of underground mains. In this system, which was originally a two-wire system, a very large amount of copper was put down in feeders, some of which were over 1,000 yards in length; but owing to the large number of feeding points, it was possible to keep the variation of pressure in the distributing mains down to as low a figure as $1\frac{1}{2}$ per cent. The system has now been changed to the three-wire with 220 volts between the outer conductors, and with an earthed middle wire; and this network of mains was the first to be provided with the fault signalling system described in chapter XVII. The cables are lead-covered jute and armoured, and are laid under the footways generally without the further protection of casing; the joints are made with clamps, and enclosed in cast-iron boxes filled with insulating oil.

In Paris a large amount of underground mains has been laid by the various companies who have obtained concessions for the lighting of the city, and very different methods have been adopted for insulating and protecting the conductors. The Compagnie Parisienne de l'air comprimé started working on a system in which a constant current was generated at a variable pressure up to 2,400 volts for charging batteries in series, these batteries supplying current to a two-wire low-pressure network of distributing mains; but this has now been modified, and continuous current transformers have been put down in the sub-stations, the secondary circuits of which supply through five-wire feeders a five-wire distributing network. The charging mains are insulated with vulcanized india-rubber, lead-covered, and served with compounded hemp, as also are some of the low-pressure mains, the cables being laid in cast-iron troughs in which are placed grooved wood casings saturated with paraffin, several

layers of these casings being often placed one above the other. A considerable portion of the distributing network was originally composed of bare copper mains, but the extensions have been made almost entirely with lead-covered and armoured cables, sometimes insulated with jute and sometimes with rubber. The bare conductors consist of uninsulated stranded cables, held by split porcelain bushes supported in blocks of oak, which are generally fixed in the cast-iron troughs above the casings containing the insulated cables. At intervals of about 100 feet or so, manholes are provided to give access to the mains; and service boxes are laid opposite the houses requiring a supply, in which the connection is made between the main and branch conductors by means of clamped joints which are left uninsulated.

The Société du Secteur de la Place Clichy supplies current at 500 volts by means of two-wire feeders and a five-wire distributing network with 110 volts on each of the four branches. Seven regulating stations are provided at various points in the network, in each of which are placed two or three dynamo regulators, which equalize the pressure on the four branches after the manner described on page 73. The cables are insulated with jute, lead-covered and armoured, and are laid direct in the ground at a depth of from 30 to 36 inches, a network of strong galvanized iron wire being laid over them to give warning of their presence to workmen who may be opening up the ground.

The cables are jointed by clamping the bare ends of the two conductors between copper clips, which are firmly bolted together. To protect the joint and to keep the exposed jute from moisture, it is enclosed in a cast-iron box, the two halves of which are securely bolted together, after which the box is filled with an

insulating compound, and as a further precaution covered outside with bitumen to prevent moisture getting in. At each street crossing distributing boxes are placed in which the connections of the various cables which meet there are made. In the box are placed two sets of copper bars, one above the other, the upper set of bars being at right angles to the lower. Each cable is connected either by copper straps or by lead fuses to one of these bars, and the corresponding bars in the upper and lower set are then connected together. The cables are brought into the distributing boxes through gland boxes which are afterwards filled up with insulating compound and covered outside with bitumen.

The Société d' Eclairage et de Force distributes current on a two-wire low-pressure system, with batteries of accumulators at the stations and at various substations. The mains consist of uninsulated stranded cables, or of bare copper strips, supported on insulators placed at intervals of about 10 feet in cement culverts. The insulators for the cables are of porcelain of the double-bell pattern, cemented to galvanized iron standards, and have a semi-circular groove at the top to receive the copper strand, which is held in place, after being strained tight, by means of iron stirrups passing over the cable and under projecting lugs on the insulators. The insulators for the copper strip are very similar, but instead of the semi-circular groove, there is a deep slot provided for the strips to rest in. Joints in the cables are made by splicing and soldering the two ends together; and the strips are connected by being clamped between iron plates bolted together, the joint being made solid by running in solder.

The Compagnie Continentale Edison distributes current on a three-wire system with 220 volts between

the outer conductors and with an earthed middle wire, and uses bare stranded cables of tinned copper wire supported on porcelain insulators, which are each fitted with a cap of galvanized cast iron with a deep slot formed in it, in which the several cables forming one conductor are laid one above the other. On each side of this cap are lugs, which serve as supports for an iron stirrup which passes round them and the cables, and keeps these latter in place after they have been strained. The insulators are fixed to bars built into the floor of a cement culvert, of which several sizes are in use, according to the number of cables to be laid in them; the largest being 17 inches wide by 14 inches deep, and the smallest 7 inches wide by 8 inches deep. In culverts which contain one or more feeders, where the conductors of the same polarity must be insulated from one another, the insulator described above is replaced by a different arrangement. A porcelain insulator with a semi-circular groove across the top is fixed in the culvert, and in this groove is laid a conductor. On this conductor is placed a porcelain block with a similar groove in both its upper and under surfaces, the groove underneath fitting as a cap over the conductor already laid, whilst the groove in the upper surface has a second conductor placed in it. Another porcelain block is then placed over the second conductor, and this may be repeated, conductors and porcelain blocks being alternately placed in position, according to the number of conductors to be carried in the culvert. As many as fifteen conductors, with an aggregate sectional area of six square inches for the three-wire main, have been placed in this manner in the largest culvert. At each of the four corners of the insulator and of the porcelain blocks is a hole through which a bolt passes. These four bolts also pass through

a bridge piece, which, when the nuts on the ends of the bolts are tightened up, is pressed down on the top conductor so as to hold all the conductors and porcelain blocks firmly in position.

House services are made with concentric rubber insulated cable laid in a grooved wood casing, the joints being made by means of clamps. Originally, two separate cables were used for services, and a great deal of trouble was experienced with them; but since concentric cables have been used, the outer conductor of which is the neutral wire, and is therefore at the same potential as the earth, this trouble has ceased.

The system adopted by the Municipality of Brussels is a continuous current three-wire system with 220 volts between the outer conductors; current being supplied to the network by three-wire feeders from the main generating station, and from two smaller stations in outlying districts, in each of which is placed a battery of accumulators, and a generating plant consisting of dynamos coupled to gas engines, which are run to supplement the supply from the main station at times of greatest demand.

The cables are insulated with vulcanized india-rubber and heavily braided, and each cable is drawn into a separate cast-iron pipe. Drawing-in and disconnecting boxes built of brick and cement lined are provided at frequent intervals, and spare pipes have been laid to facilitate the drawing-in of additional cables without further disturbance of the street surface. In the disconnecting boxes, of which there are a large number, the cables have tinned lugs sweated to their ends, and these lugs are threaded on to gun-metal bolts and firmly bolted together. After the lugs have been sweated on, the rubber insulation is cut to a bevel so as to expose a clean surface, and the bared conductor is

tightly taped with vulcanizing rubber strip, which extends over the shank of the lug and over the bevelled surface as far back as the braiding. This rubber strip is painted with several coats of anti-sulphuric enamel, and when the lugs have been bolted together, the whole connection is painted with enamel. All connections, other than those in the disconnecting boxes, are made with soldered joints insulated with rubber and vulcanized, and services are made with rubber cables in iron pipes, the tee-joints being soldered and vulcanized in small brick service boxes.

In America, the majority of the low-pressure work has been done by the Edison Company, or by local companies formed to work their system. In most cases the mains consist of Edison tubes arranged for a three-wire distribution, made and jointed in the manner described in chapter X., but several of the local companies use continuously insulated cables instead of the tubes. Since its first introduction, there have been many improvements made in the Edison underground system, not only in the details of the tubes themselves and of the joint boxes, but also in the design of distributing boxes and junction boxes. These boxes are specially designed so as to afford facilities for breaking up long mains into comparatively short sections, as an aid to localizing faults. They are made of cast iron with double covers, the inner one being made water-tight by a rubber gasket; and contain insulated blocks to which the ends of the conductors are connected, the junctions between these blocks, required to complete the continuity of the circuit, being made by means of removable copper strips. When the feeders are of considerable length, as is often the case, several of these boxes are inserted, to divide them up into sections; and where more than one feeder main passes

through the box, provision is made for cross connections, so that if one section of a feeder is faulty, it is not necessary to cut out of circuit the whole length, but only the bad section, the remaining feeders in this section being connected up to carry the whole current.

The London Electric Supply Corporation.

This company's system differs from most others at present in use in England, in that an extra high pressure is employed, with a double transformation between the generating station and the lamps. According to the original design, the current which is generated at Deptford is to be conveyed at a pressure of 10,000 volts to four transformer stations at Blackfriars, Pimlico, Bond Street, and Trafalgar Square, and distributed from these stations at 2,400 volts to a number of transformers, from which the consumers' premises are to be served by means of low-pressure distributing networks. At present this plan has not been carried out fully, owing to the fact that the houses taking current are too much scattered, and there are therefore comparatively few cases in which a low-pressure distributing network is employed, the general plan being to fix the 2,400 to 100 volt transformer on the consumer's premises; but it is intended, as the demand increases, to arrange for sub-stations, each of which will serve by low-pressure mains the houses in the immediate neighbourhood. The complete system of mains, etc., will then be as shown in Fig. 100, where A is the dynamo machine at Deptford, B is one of the four main transformer stations, C a transformer sub-station, H, H, H, consumers' premises, E, E, E, earth connections, and SD, safety devices. The 10,000 and 2,400 volt mains are concentric, and,

for the reasons mentioned in a preceding chapter, the outer conductor of each is connected permanently to the earth, the one at the dynamo terminal, and the other at the secondary terminal of the transformer. The transformer cases are also connected to earth. The inner conductor of the 2,400 volt main, and both conductors of the low-pressure main, are connected to a safety device, such as the Cardew earthing device, which will connect the conductor to earth, should the

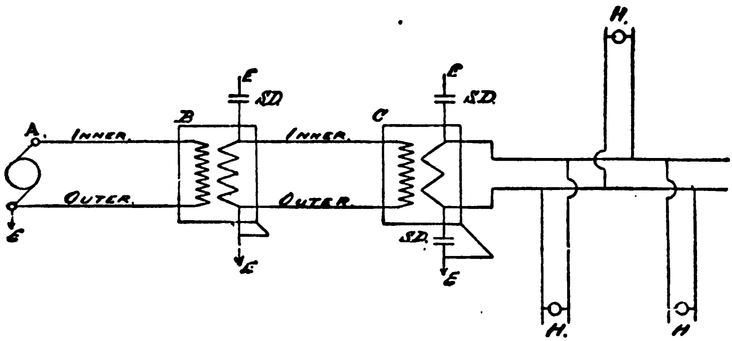

FIG. 100.

difference of potential between them exceed a certain fixed amount, owing, say, to a breakdown of the insulation between the primary and secondary circuits of the transformer.

To protect themselves against accidents which might arise from faults in the house wiring, the engineers of this company have devised an automatic switch, which, in addition to earthing both conductors, when the difference of potential between them and the earth becomes too high, also does so when the insulation of the house circuit falls below a fixed amount. This

apparatus is shown diagrammatically in Fig. 101. The primaries of two small transformers are connected in series across the house mains *a* and *b*, and the junction between them is connected to earth at E. The secondaries of these transformers are connected in series, but in such a manner that they oppose one another, and are short-circuited through a fuse wire *cd*, on which a weight W is hung. So long as the pressures be-

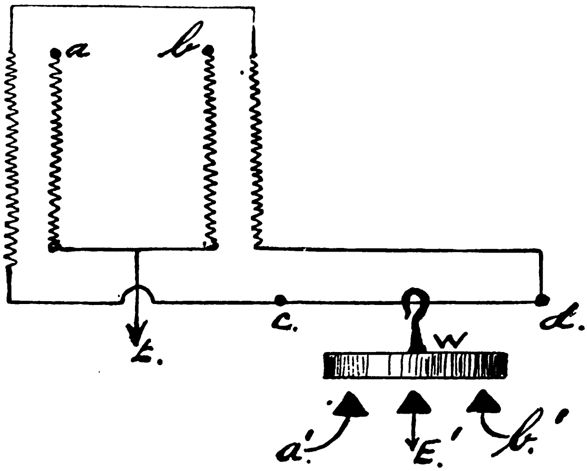

FIG. 101.

tween *a* and earth and *b* and earth are equal, the electro-motive forces in the secondaries will be equal and opposite, and no current will flow through the fuse wire; but if the balance is disturbed by a heavy leak to earth from either *a* or *b*, or by the insulation between the primary and secondary of the 2,400 to 100 volt transformer breaking down, and raising the pressure at one terminal, a current will be produced in the secondary circuits of the safety transformers,

and the fuse will be broken. This will cause the weight W to drop, and make connection between the three blocks a', b', and E′, which are connected respectively to the two sides of the house circuit and to earth, thereby short-circuiting the house mains, and causing the main fuse to blow, thus disconnecting them from the supply circuit; at the same time connecting them both to earth, so as to make it impossible for any shock to be received from a contact with them.

The 10,000 volt current was originally transmitted from Deptford to London by means of four Ferranti concentric mains, made and jointed in the manner described in chapter X., but owing to the trouble experienced with this class of main, the London Electric Company decided to replace them by continuously insulated cables, and has at the present time already replaced about three-quarters of the total length of main. The cable used for the most part is a concentric cable, insulated with paper and lead-covered, but some part of the old mains has been replaced by the "Hygroscopic" cable recently brought out by Messrs. Siemens. These cables are laid underground in cast-iron pipes, in which at intervals of 1,000 yards, or less, testing boxes are provided. These boxes have outlets at each end through which the mains are introduced, the joint between the iron tube and the outlet being made tight by caulking. The conductors are connected by clamps, which are arranged so that the contact can easily be broken, and the box is filled up with a heavy insulating oil.

The localizing of a fault in one of these mains is effected in the following manner, the apparatus used being a slide bridge galvanometer, and one or two cells capable of giving a fairly large current. At the time of smallest demand, when the load can be

supplied by the other mains, the inner conductor of the faulty main is looped with the inner conductor of a good main (Fig. 102), and the battery, galvanometer, and slide wire are connected up so as to form a bridge, the four points of which are A, B, C, and the fault F. The ratio of the resistances AF : FB can then be found, and from the known resistance per unit length the distance AF can be calculated, the result of the test invariably giving the correct position within 50 yards. This shows in which

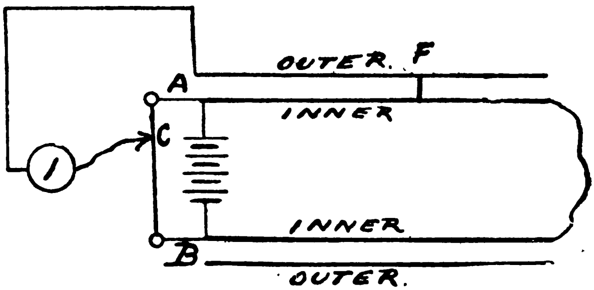

FIG. 102.

section of the main the fault is, and a further test is then made at the test boxes on the faulty section, which generally gives the position within 5 yards.

The 2,400 volt mains are concentric cables, insulated with paper or jute, lead-covered and armoured, but there are also some lead-covered unarmoured cables, and some vulcanized india-rubber cables, these latter being the cables which were in use underground when the generating station was at the Grosvenor Gallery, and which have been taken up and made concentric. The armoured cable is laid in a trench without further protection, and the joints are made in boxes filled up

with oil; the other cables are sometimes jointed in the same way, and sometimes by making the ordinary soldered joint, and insulating it in the manner already described.

The Metropolitan Electric Supply Company.

This company, distributing current over a very extended area, adopted as a pioneer system the alternating current transformer system with the transformers in the houses, and equipped stations with the necessary plant at Sardinia Street, Rathbone Place, Manchester Square and Amberley Road, Paddington. The pressure adopted was 1,000 volts, and cables insulated with vulcanized india-rubber were laid on the loop system, being drawn into cast-iron pipes provided with manholes to facilitate the drawing in or out of the cable, and with split T pieces for making connections to consumers' premises. This system of mains is probably the most perfect example of a drawing in and out system, as there are no T joints in the cables, and the mains are laid in such a manner that individual sections can be disconnected, drawn out, and replaced, without interfering with the supply of current to any consumer. The general arrangement is shown diagrammatically in Fig. 103, where A and B are the terminals of the dynamo, and H_1 H_2, etc., the primary terminals on the consumers' premises. From A a length of cable is laid to the terminal of the primary fuse at H_1, and from H_1, another length is laid to H_2, and so on, H_4 being connected by a cable to A. In a similar manner a complete loop of cable is run from B, calling in at each consumer's and back to B again.

The T joint, by means of which the service wire is generally connected to the main, is thus done away

with, the circuit being completed by running the main cable into the house and out again. This of course necessitates the use of rather more cable; but, as the mains are generally laid under the footway, the distance from them to the primary fuse boxes, which are placed in the cellars, is very short; and the cost of the extra cable is in most cases found to

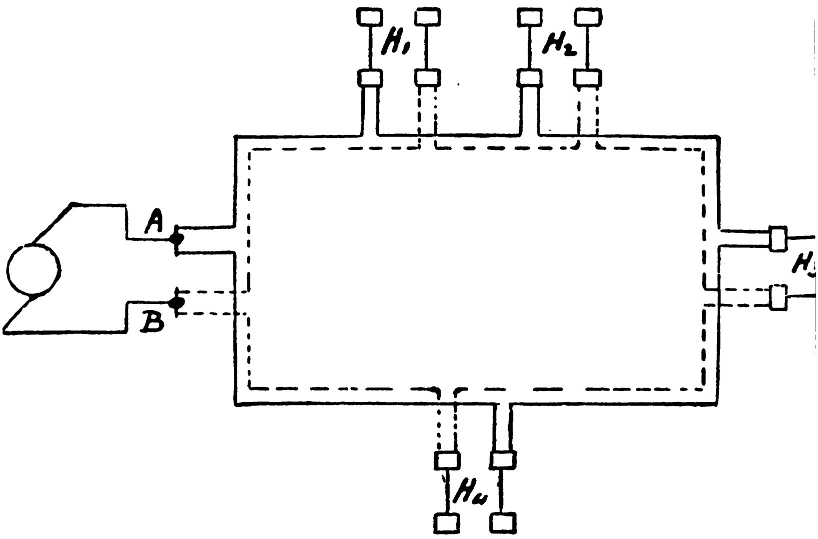

FIG. 103.

be less than that of making two reliable T joints. Apart, however, from the question of cost is that of convenience, and in this respect the arrangement of mains adopted has great advantages. It will be seen that each consumer is supplied with current by two routes, H_3, for instance, being connected to the dynamo by the cable going to H_4 as well as by that which goes to H_1 and H_2; and therefore it is possible to

disconnect the length of cable joining two consumers, say H_2 and H_3, without stopping the supply of current to either. This facilitates very much the localization and repair of a fault; as, supposing that the tests at the station show that there is a fault on the circuit, it is easy to find out in which section it is by disconnecting each one in turn, and testing it separately; and when the faulty section has been found, it can be drawn out of the pipe, and a fresh length of cable drawn in, whilst the remainder of the circuit is working. Again, if connections have to be made to a new customer, say between H_3 and H_4, the section joining these two is pulled out, and is replaced by two shorter sections: one from H_3 to the new premises, and one from them to H_4; H_3 and H_4 receiving their supply of current in the meantime, the one by the upper cables in the diagram, and the other by the lower ones.

The generating stations are connected by trunk mains, consisting of vulcanized rubber or lead-covered paper cables, to enable one station to supply current, when necessary, into the district of another one.

This pioneer system has worked well and was the most practical system in the early days of the undertaking; but as the demand for current has increased, the system has been modified, and portions of the districts, where the lamp density is sufficient, are supplied from transformer sub-stations, the transformers being fed with high-pressure current from the original rubber cables and distributing low-pressure current by means of triple concentric cables insulated with paper and lead-covered. These sub-stations are above ground, and the low-pressure network is subdivided into sections, so that it is easily controlled.

In addition to the modification of the alternating

current system described above, a further development is in progress which consists in supplying the three-wire low-pressure network in some of the home districts by means of low-pressure continuous current feeders. This, however, is only part of a much more important change of system, which is now being made, and which consists in the erection of a large generating station at Willesden, outside the company's area of supply, at which two-phase currents will be generated at a pressure of 500 volts on each phase. The pressure will be raised by step-up transformers at Willesden to 10,000 volts, at which pressure current will be transmitted to various sub-stations in the company's area, and there converted by motor generators into direct currents for distribution to the consumers.

A first portion of the generating and transforming plant is already erected at Willesden and is supplying current, but at present the 10,000 volt current is transformed down at the sub-stations to 1,000 volts, and is distributed by means of the existing network of alternating current feeders and distributors. As the substitution of direct current for alternating current distribution is extended, motor-generators will be erected in the sub-stations to convert the two-phase currents into direct currents.

The high-pressure mains connecting the sub-stations to Willesden are concentric cables, the outer conductors of which are earthed at the station. Five of these cables are laid, and as independent concentric cables are used for each phase there are thus a duplicate set of cables, and one spare one, which can be switched on to either phase as may be required. These cables are insulated with paper and lead-covered, and are laid in a five-duct cast-iron conduit, part of the route being

along the tow-path of the Grand Junction Canal and part through the streets. Along the tow-path the ducts are filled in with pitch around the cables, but in the streets sawdust is used. The joints in these cables are soldered, insulated with cotton tape boiled in rosin oil alternating with layers of mica, and covered by a lead sleeve. This lead sleeve, which is drawn over the cable end before the joint is made, is slid down into place and soldered to the lead covering on either side of the joint, after which the space between the insulated joint and the sleeve is filled up with insulating compound.

Disconnection boxes are fixed at intervals to facilitate testing. These boxes are divided into an upper and a lower half by an ebonite plate, and the cables are brought into the lower half through glands filled up with compound. The ends of the cables are trimmed in the manner described in chapter X., and connectors carrying studs, which pass up through the ebonite plate, are then clamped on to the inner and outer conductors, and the lower half of the box is filled up with insulating oil. The link for connecting the two outer conductors rests on the ebonite plate, but the studs connected to the inner conductors project some way through this plate and are surrounded by a corrugated ebonite collar, which comes between the ebonite plate and the link, and thus decreases considerably the surface leakage.

The House-to-House Electric Light Supply Company.

This company supplies current on an alternating current transformer system, the current being generated at a pressure of 2,000 volts. In the early years of working the transformers were all on the con-

sumers' premises, and were supplied with current from a high-pressure network consisting of vulcanized rubber cables laid in cast-iron pipes, the junctions being made in cast-iron surface boxes by soldering the conductors together and insulating the joints with india-rubber, which was then vulcanized. At the present time this system has been modified, and low-pressure distributing networks, in connection with transformers in sub-stations or street boxes supplied by high-pressure feeders, form part of the system. Changes have also been made in the class of cable used, as those laid in the last few years are insulated with paper and lead-covered, and a special type of disconnecting box, for cutting out any portion of the high or low tension mains, has been adopted.

THE CITY OF LONDON ELECTRIC LIGHTING COMPANY.

The system employed by this company for private lighting is a high-pressure alternating current transformer system, the current being transmitted at a pressure of 2,000 volts from the generating station to transformers in sub-stations, and thence distributed to the consumers by a three-wire distributing network with 200 volts between the outer conductors. The arc lamps for street lighting, of which there are about 600, are supplied with current on the direct current series system, the pressure at the dynamo terminals being from 2,000 to 3,000 volts according to the number of lamps in series on each circuit.

Although several types of cable are used, including paper, rubber, and bitumen insulated conductors, the quantity of the two last is relatively small, and the standard type is a cable insulated with paper and lead-covered. The high-pressure cables for private lighting are concentric, whilst those for the arc light-

ing circuits are twin wire cables; they are drawn into wrought-iron pipes, laid as much as possible under the footways, and provided with brick drawing-in boxes at frequent intervals. The use of wrought-iron pipes, which are not so durable as those of cast iron, was adopted because of the facility with which they could be bent on the spot, and their alignment altered so as to get past the many obstructions existing under the footways of the city.

The low-pressure cables are for the most part triple concentric paper-insulated and lead-covered cables drawn into wrought-iron pipes, but there are also some single cables insulated with bitite and drawn into bitumen casing sheathed with iron. The drawing-in boxes are of brick, and the service boxes of cast iron placed in small brick boxes; the joints between the service wires and the distributors are made by gun-metal clamps, after which the cast-iron boxes are filled up with an insulating oil or compound.

The County of London and Brush Provincial Company.

This company supplies current to several large districts on both sides of the Thames, and has at present two generating stations: one in the City Road, serving the parishes of St. Luke and Clerkenwell, and portions of several parishes lying to the west of them; and the other in Wandsworth, serving Putney, Wandsworth, Clapham, Streatham, and Camberwell. The company do not confine themselves to one system of supply, but have supplemented the single phase alternating current system with which they commenced by the addition of continuous current circuits in one district, of two-phase alternating

current circuits in others, and of an extra high-pressure transmission to the outlying districts supplied from their Wandsworth station.

At the City Road station alternating currents are generated at a pressure of 2,000 volts, single phase currents being used for lighting in the Clerkenwell and St. Luke districts, whilst two-phase currents are used for both lighting and power in the outlying districts supplied from this station. The high-pressure currents are transmitted by concentric cables insulated with paper, lead-covered, and drawn into cast-iron pipes, to transformers placed in ventilated boxes under the streets, where the pressure is reduced to 100 volts. The distributing mains consist of lead-covered concentric cables insulated with jute and bitumen, which are drawn into iron pipes and are provided with two-way service boxes at every fourth house, in which services are made with clamped joints. In Clerkenwell and St. Luke, where single phase currents are used for lighting, special mains are laid for a power service which are supplied with a continuous current at 530 volts. These mains consist of concentric cables insulated with vulcanized rubber drawn into cast-iron pipes, the service connections being made with soldered joints insulated with rubber, which is vulcanized *in situ.*

At the Wandsworth station both single and two-phase currents are generated at 2,000 volts, the latter being used in districts where a demand for power is expected, and the former in districts where a lighting load only is anticipated. In what may be called the home districts, current is transmitted at 2,000 volts from the station to transformers placed in boxes under the streets, where the pressure is reduced to 200 volts for distribution to consumers. Owing to the very

extensive area supplied from this station, 2,000 volts is not a high enough pressure for economical transmission to many parts of the district; and an extra high-pressure service has therefore been provided by installing step-up transformers at the station, which raise the pressure from 2,000 to 6,000 volts, at which pressure the current is transmitted to transformers placed in stations above ground, where the pressure is again reduced to 2,000 volts. From each of these main transformer stations current is distributed on the same system as that employed for the home district. The cables for both the 6,000 and 2,000 volt circuits are concentric cables insulated with vulcanized india-rubber, and sheathed with steel tapes; and those for the low-pressure distributing mains are lead-covered jute cables, both classes of cable being drawn into iron pipes.

Islington.

The system of distribution adopted at Islington is a high-pressure alternating current transformer system, current being transmitted at a pressure of 2,000 volts from the generating station to transformers placed in tanks under the pavements, and distributed from them to the consumers at a pressure of 100 volts in some parts of the district and 200 volts in others. In a few cases, where the demand for current by any individual consumer is great enough, a transformer is placed on his premises. The arc lamps for street lighting are run in series on circuits supplied with a rectified alternating current, the cables used being similar to those employed for the primary circuits to the transformers.

These high-pressure cables are concentric, insulated between the inner and outer conductors and between

the outer and earth with vulcanized india-rubber, and then armoured with two steel tapes and further protected by a heavy braiding impregnated with preservative compound. These cables are drawn into cast-iron pipes provided with drawing-in boxes at intervals, and the circuits are so arranged that each conductor forms a complete metallic loop, starting from and returning to the generating station. In each drawing-in box a small amount of slack is left, and when an additional transformer has to be connected in the circuit, the transformer tank and a switch-box are fixed below the pavement alongside a drawing-in box, and the cable in the drawing-in box is cut and the two ends are taken through a short connecting pipe to the switch-box. This latter is fitted with three terminals for the inner conductors, and three others for the outer conductors of the cables entering the box; two of each set being for the cables coming from the drawing-in box, whilst the third in each set is for the cable going from the switch-box to the transformer. There is also a bus bar for each pole of the circuit, the bar for the inner conductors being connected by plug switches to the terminals of the two inner conductors coming from the drawing-in box, and by a fuse to the terminal of the inner conductor going to the transformer, whilst the bar for the outer conductor is connected by plug switches to the three terminals of the outer conductors.

This system of mains is shown diagrammatically in Fig. 104, in which, to avoid confusion, only the inner conductor is drawn. The conductor is connected at each end of the loop to the terminal O of the station switch-board; A, B, and C are the drawing-in boxes, S S S the switch-boxes, and T T T the transformers. It will be seen that, if it is required to disconnect any

section of the high-pressure cable, say between A and B, from the circuit for testing or repairs, this can be done by withdrawing the plug switches connecting the two ends of this section to the bus bars in the switch-boxes at A and B; and that no interruption of the service is caused by this, since the transformer at A is still supplied with current through the cable

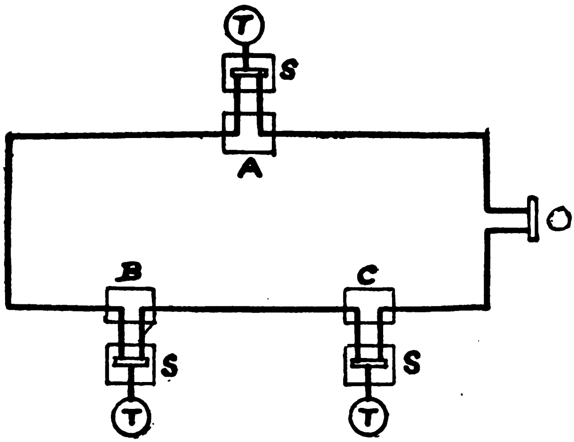

FIG. 104.

which comes direct from O, whilst that at B is supplied through the cable coming from O through C. The circuit of the outer conductor is arranged in exactly the same manner, so that if the corresponding plug switches in A and B are withdrawn, the section of the concentric cable between A and B is entirely isolated from the circuit.

The outer conductor of each concentric main is connected to earth through a switch at the generating

station, so that the earth connection can easily be broken when necessary for testing.

The low-pressure distributors are also concentric cables insulated with vulcanized india-rubber and armoured with steel tapes, but they are drawn into earthenware pipes to protect them from accidental damage. Watertight service boxes are provided at short intervals, in which connection between the distributors and service wires are made through fuses, each box being fitted with terminal blocks for several service connections.

Bristol Corporation.

The system employed at Bristol is a high-pressure alternating current transformer system, current being transmitted at a pressure of 2,000 volts from the generating station to transformers in sub-stations, of which there are more than thirty, and distributed thence to the consumers by three-wire low-pressure distributors with 210 volts between the outer conductors. The high-pressure cables are concentric cables insulated with jute or paper, lead-covered and armoured with two steel tapes, and are laid direct in the ground, mostly under the footways, and covered with a layer of bricks. The distributors are triple concentric cables, insulated and laid in a similar manner. For the arc light circuits the cable is partly concentric, as described above, and partly single, the armouring in the latter case being of steel wires instead of tapes.

Leeds Corporation.

The system taken over by the Corporation from the Yorkshire House-to-House Electricity Company at Leeds is a high-pressure alternating current transformer system. As first carried out, the current was

distributed at high pressure with transformers in the houses, but recently low-pressure networks have been laid, fed from transformers in sub-stations under the road.

The high-pressure cables are either single cables insulated with vulcanized india-rubber and drawn into cast-iron pipes, or concentric cables insulated with paper, lead-covered and armoured, and laid in the ground in wooden troughing filled in with bitumen, with a course of loose bricks over the troughs as a further protection. No mechanical joints in boxes are made in the high-tension cable, those in the rubber cables being soldered and insulated with vulcanized rubber, and those in the paper cables being soldered and re-insulated, and protected as in the cable, and then compounded outside with bitumen.

The low-pressure cable is triple concentric insulated with paper, and lead-covered but not armoured, and is laid in troughs filled in with bitumen, and protected by a course of bricks, service connections being made with clamps in cast-iron boxes filled with insulating material.

The Newcastle-upon-Tyne Electric Supply Company.

This company supplies current on a high-pressure alternating current system at 2,000 volts, with transformers in the houses; but has also some transformers in sub-stations with low-pressure distribution. The cables used are concentric cables insulated with vulcanized india-rubber, and drawn into cast-iron pipes, each cable having a separate pipe. Junction and service boxes of cast iron are provided, in which mechanical joints are made. The concentric cable is brought into the box, and the outer insulation is stripped off for a length of nine or ten inches; the

outer conductors are turned back and twisted together so as to form a strand conductor, which is re-insulated with rubber; and each conductor is clamped into a connector. Two porcelain insulators are fixed in the box, each insulator being fitted with a gun-metal stud, on which the connectors of cables of the same polarity are threaded and clamped together by a nut on the stud. This arrangement greatly facilitates testing and the localizing and repair of any fault which may develop in the mains.

The Newcastle and District Electric Lighting Company.

The system employed by this company is the alternating current transformer system, current being generated at 1,000 volts and transmitted to transformers on the consumers' premises, or in some cases in sub-stations. The cables used are single cables insulated with vulcanized india-rubber, braided and extra taped, and drawn into cast-iron pipes, carefully laid and lead-jointed so as to render them as nearly gas- and water-tight as possible. At intervals cast-iron boxes are provided to facilitate the drawing in of cables and the jointing on of branch cables. These boxes are also made tight, the covers resting on a rubber ring and being secured by gun-metal bolts; and as an additional precaution a blower at the generating station keeps a slight pressure of air on the inside of the whole system of pipes and boxes. All joints, both straight and tee, are insulated with rubber and vulcanized *in situ*, and services are led away from the boxes in lap-welded steam piping screwed into the sides of the box.

Portsmouth Corporation.

The system adopted at Portsmouth for private lighting is an alternating current transformer system, cur-

rent being transmitted at 2,000 volts to transformers in street boxes, and thence distributed by a two-wire network of low-pressure mains; whilst for the public arc lighting circuits a rectified current is used. The cables used are vulcanized rubber cables laid in iron conduits, and lead-covered paper cables laid in troughing, filled in with compound and protected by a layer of bricks above it. The high-pressure cables for feeders and arc lighting were originally concentric, and the low-pressure cables single; but for the arc light circuits twin cables have now been substituted for the concentric.

Continental and American High-Pressure System.

On the Continent a considerable number of stations, working on the alternating current transformer system, have been erected by Messrs. Ganz & Co.; some with overhead wires, and some with underground; the former being used in some of the smaller towns, and also for the feeders from stations placed outside the town, to the town itself; and the latter in the larger towns. The overhead wires are attached to ordinary double-bell or fluid insulators, and the underground mains are usually concentric cables insulated with jute, lead-covered and armoured, though in some few cases rubber cables are used. In most cases transformer stations are used, from which the consumers are supplied by a low-pressure network, the best example of this being the installation at Rome. Concentric cables insulated with impregnated jute, lead-covered and armoured, are laid in a wooden box filled with cement, and the joints are made with clamps in cast-iron boxes (Fig. 105), which are afterwards filled up with an insulating oil.

At Madrid and Barcelona, installations have been carried out on the alternating current system with

transformers on consumers' premises, vulcanized rubber cables being drawn into iron pipes, and the joints insulated with india-rubber and vulcanized.

At Havre there is an installation on the Ferranti system, in which underground cables are worked at a pressure of 2,400 volts. These cables are insulated with vulcanized india-rubber, lead-covered and armoured, and are laid in the ground without further protection. The joints were originally made by clamping the conductors together, wrapping them with india-rubber strip, and enclosing the whole in a cast-iron box, which was filled up solid with bitumen. These joints, how-

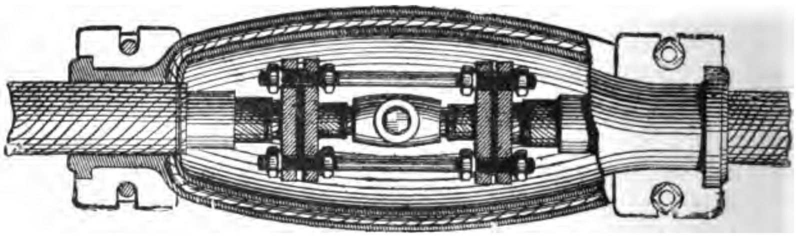

FIG. 105.

ever, gave a great deal of trouble, and they have all had to be re-made; the method adopted being to make a soldered joint, insulate it with india-rubber and vulcanize it; and these joints have been found very satisfactory, and are working well.

The high-pressure circuits in America, both for arc lighting in series, and for incandescent lighting by the transformer system, are more often overhead than underground; but of late years, owing to the objections raised in most of the larger towns to the use of overhead wires, a considerable mileage of underground conductors has been laid. The city of Chicago was one of the first to insist on underground work; and at the present time there are no overhead electric light

circuits in the city itself, which is divided up into twelve districts, each to be supplied from a station as near the centre as possible. The plan of distribution is to build a main subway extending right across the district, with branches running out at right angles, and reaching to the other boundary lines. Various conduits are used; iron pipes laid in the ground or in concrete, cement-lined iron pipes in concrete, and the Dorsett conduit, all being employed; into these conduits are drawn cables, either insulated with rubber mixtures such as kerite, okonite or vulcanite, or with fibrous material enclosed in a lead tube. The conduits are provided with rectangular brick manholes placed from 80 to 150 yards apart. The Chicago Arc Light and Power Company operates over 2,000 arc lamps by means of underground cables, some of which are Patterson cables, insulated with fibrous material impregnated with paraffin to a thickness of $\frac{3}{16}$ths of an inch, and drawn into a lead pipe; and some, Norwich cables insulated with paper to a thickness of $\frac{5}{32}$nds of an inch, and lead covered. The joints, which have been the chief cause of trouble, more especially with the paraffin cable, from which it has been found difficult to exclude moisture, are made by soldering the two ends of the conductors into a copper sleeve, covering the joint with insulating material, and moulding over it a solder connection from lead to lead. A large portion of their conduit is of the Dorsett type; but they also use $2\frac{1}{2}$-inch wrought-iron pipes, and a conduit made of pine logs $4\frac{1}{2}$ inches square outside, and bored lengthwise with a circular hole $2\frac{1}{2}$ inches diameter (see Figs. 79, 80). The average pressure on these arc lighting circuits is 2,500 volts. Besides the underground circuits in the city itself, this company has some 80 miles of overhead circuits, outside the city boundary,

which are used for arc lighting, the pressure in some cases reaching as high as 4,000 volts. The overhead wire is covered with a triple braiding, is supported on glass insulators attached to the pole arms, and is protected by lightning arresters of the Thomson-Houston type fixed at both ends of each circuit in the station.

The Westinghouse Company, who have done a very large share of the work in connection with incandescent lighting on the alternating current transformer system, as well as arc lighting in series with both continuous and alternating currents, use for the most part overhead wires; some of which, on arc light circuits, carry current at a pressure as high as 5,000 volts. The cables are supported without bearer wires on insulators attached to the pole arms, the spans being arranged in such a manner that there is practically no danger of the conductor breaking. All the circuits are protected by their special types of lightning arrester, of which descriptions were given in chapter XIII. The highest pressure employed on any of their incandescent lamp circuits is 4,000 volts, at Portland, Oregon; where they have a plant working with a double transformation. The generating machinery is driven by water power at a station situated 12 miles from the city, and supplies current at 4,000 volts to sub-stations in the city, where it is reduced to 1,000 volts; at which pressure it is distributed to the transformers on the consumers' premises, and there it is further reduced to 50 volts. The maximum pressure usually employed on the incandescent circuits is 1,000 volts.

When underground cables are used, they are always lead-covered, and are of one of three types, viz.: the Standard cable, insulated with fibrous material impregnated with compound; a cable insulated with soft rubber; or a cable insulated with vulcanized

rubber, the rubber being separated from the lead by a layer of paraffin. In some cases, especially for feeders, a duplex cable is used, in which the two insulated conductors are enclosed in the same lead casing. These cables are drawn into iron pipes, or cement-lined sheet-iron tubes, laid in cement and provided with manholes for giving access to the cables. Joints are made by soldering the conductors into a metal sleeve, wrapping them with tapes or rubber strips, and covering the entire joint with a lead sleeve wiped on to the lead armouring with a plumber's joint. All these types of cable are working well, the chief cause of trouble, when there is any, being the failure of a joint; but when this occurs it is usually detected by the insulation tests before it causes any interruption of the service.

The Thomson-Houston Company's system of distribution, whether for arc lamps in series, or for incandescent lighting by alternating current transformers, is mostly carried out by means of overhead wires, continuously insulated and supported on glass insulators on the pole arms. The transformer circuits are usually supplied with a primary pressure of 1,000 volts, which is reduced in the secondary circuit to 52 or 104 volts. The circuits are protected by lightning arresters in the station, and are generally arranged so that feeders are run to various points, which form centres of distribution, and at which fusible cut-out boxes are fixed on the poles. From these cut-out boxes are branched off the distribuing mains, which are of such a section that the loss of pressure is only about one half per cent. To these mains, just before they arrive at the transformer, is connected a lightning arrester; and on the secondary side of the transformers is fixed a safety device, which has been designed by the company to

protect any person, touching the secondary conductors, from the possibility of a shock, due to the introduction in the circuit of a higher pressure than the normal working one. This apparatus consists of three insulated terminal blocks, the central one of which is connected to earth, whilst the outer ones are connected to the secondary conductors. A flat brass spring is attached to the middle block, in such a manner that each end of it is pressed up against one of the outer blocks; from which, however, it is separated by a thin paper film, prepared so that it will withstand the strain due to the ordinary working pressure, but will be pierced as soon as the pressure between the secondary terminal and earth reaches a previously determined value. If the insulation of the circuit is faulty so that a shock would result from contact, the connection to earth, which is made as soon as the paper is pierced, short circuits the secondary and causes the primary fuse to blow, thus cutting the transformer out of circuit.

CHAPTER XVII

Testing Cables during Laying and Jointing.—Testing Completed Installations.—Difficulties with Earthed Systems and Concentric Cables.—Testing Installations when Working.—Lamp Test.—Vacuum Tube Indicator.—Recording Voltmeter.—Bridge Test with Working Current.—Use of Voltmeter or Ammeter for Measuring Fault Resistance and Leakage Current of Network.—Determination of Fault Resistance of Separate Conductor.—Testing of High-Pressure and Alternating Current Circuits.—Testing of Earthed Systems.—Use of Voltmeter for measuring Fault Resistance of House Circuits or Sections of Network.—Localizing Fault by Voltmeter Test.—Berlin Pilot Wire System of Fault Signalling.—Localizing Faults by Induction Coil; by Transformer; by dividing Network into Sections; by Two Station Method; by Differential Ammeter; by Loop Test; by Search Coil and Telephone; and by Compass.

THE importance of a complete system of testing cables before they leave the factory has already been referred to; and we have now to deal with an equally important subject, namely, the testing of the cables after delivery, and of the complete installation after it has started working. This is a matter which is too often neglected, with the result that a fault, which might quickly be localized and repaired if each section were tested as the work proceeds, may be difficult to find if no tests are made until the whole installation is completed; or again, that after the circuit is in use a small fault, which might easily be repaired, is allowed to develop into such a serious one that it interferes with

the working of the circuit, and causes a breakdown. When we consider the chances that occur of injuring the cables, mechanically or otherwise, during the laying of underground mains, or the erecting of cables overhead, or in buildings; it must be evident that continual testing is necessary, if we are to make certain that the work is done properly; and, as it is much easier to trace a fault immediately it has been caused, and when it is pretty well known what section of the work it is in, than it is when there is no guide as to its whereabouts, it is important that tests should be made regularly as the work proceeds. For instance, suppose that a system of underground mains is being laid, the work is done in sections, and the several sections are afterwards jointed together. Now, if each section, as it is laid, is tested, and if a test is made on the mains, before and after the joints are made which connect on to the system another section of cable, any fault which has been caused in laying can generally be traced pretty easily; whereas if half a dozen sections are joined together before a test is made, it becomes very difficult to localize a fault; indeed, it is probable that, before this can be done, the joints which have just been made may have to be unmade, and the several sections separated again.

The tests, which should be made during the laying and jointing of cables or the wiring of buildings, are the same as those made in the factory, and the methods of making them are similar to those described in chapter XI. The conductor resistance and capacity of the cables are frequently not measured again, the former test being of importance only as showing that there are no faulty connections or joints, and, in the case of small house wires, that the conductor has not been broken; whilst the capacity of

the cables is only of interest in the case of an extended system of high-pressure alternating current mains. Tests of the insulation resistance of the cable and of its resistance to disruptive strain are, however, of the first importance, and should never be omitted. Separate tests of the insulation resistance of each conductor from earth, and of one conductor from another, should be made when two or more separately insulated conductors are used, and are laid in such a manner that leakage can occur between two conductors without the earth forming part of the leakage circuit; but tests between conductors are not necessary if, for example, each cable is covered with a metallic sheathing, which is in connection with the earth; and with concentric or triple concentric cables it is not necessary to measure the insulation to earth of more than the outside conductor.

During the laying and jointing of the cables, the insulation tests may be made in the manner described in chapter XI., either with a reflecting galvanometer and other apparatus, as used in the factory, or, when this cannot be done, with some form of portable testing apparatus. The former apparatus may, and should always be fitted up in the test room of every central station; whilst for outdoor work, or for testing the insulation of installations in buildings and ships, a portable testing set should be provided. This latter apparatus may be obtained in various forms, a convenient one being a small box containing a sensitive galvanometer provided with two or three shunts, a standard resistance for taking the constant, and the necessary terminals and keys. With this test box there should be provided a battery of small testing cells, fitted in a separate box, in number sufficient at the least to give a pressure of about 50 volts for in-

door work, and 200 volts for testing underground or overhead mains. Another form of portable apparatus, which is frequently used, consists of an ohmmeter suitable for measuring high resistances, and a magneto machine, which should be capable of giving a pressure of about 200 volts.

The test for resistance to disruptive strain should be applied to all high-pressure mains after they are laid and before they are put in regular service, and should be made by subjecting the cables to at least twice the normal working pressure. Where continuous currents only are available, the making of this test presents some difficulty, as the apparatus must consist of a dynamo wound to give the necessary pressure coupled to an electric or other motor; and this cannot easily be made portable. With alternating currents, however, a step-up transformer, the primary circuit of which is wound to suit the normal working pressure, and the secondary to give a pressure at least twice as great, can be used; and this apparatus need not be very bulky, if the mains are tested in comparatively small sections at a time. This apparatus may be installed in the generating station, or if it is desired to test a new section of main which is at some distance, it can be used in the street, the primary circuit being connected to the main already in use, and the secondary to the new mains which are to be tested.

When the installation is completed, and the lamps and other receiving apparatus connected up, it is no longer possible to measure directly the insulation resistance between the two conductors, since the conducting bridge formed by the lamps has a much lower resistance than that of the leakage circuit, and any measurement therefore would give practically the resistance of the lamps, and not the insulation of the

cables. The insulation of the cables from earth can however always be measured, except when one conductor is permanently connected to earth, or when concentric cables are used; and, if the mains are laid in such a manner that no current can leak from one conductor to the other, without the earth forming part of the leakage circuit, we can always tell that the insulation between the two conductors is higher than that between the conductors and earth; because, in the latter case, the fault resistances of the two conductors are connected in parallel, whilst, in the former, they are in series with one another.

Herein lies one great advantage of a double-wire system, when arranged in such a manner that each cable is surrounded by a good conductor connected to earth; as, for instance, when the cables are in water, or are armoured, or when each cable is enclosed in a metal pipe, the pipe and armouring being earthed; since, under such conditions, any leakage must in the first instance be from a conductor to earth. On the other hand, if an earthed system is employed, there is no way of ascertaining the state of the insulation, unless all the lamps are disconnected; and the same holds good with any system of concentric wiring, since the state of affairs then is that there can be no leakage to earth from the inner conductor, unless the outer conductor forms part of the circuit. Of course, if the double-wire system is arranged so that no conductor connected to earth is interposed between the two cables, as when they are both laid together in a semi-insulating conduit, or even when they are laid in separate grooves in wood casing, it is quite possible that the insulation resistance from one conductor to the other may be lower than that between either conductor and earth.

With this method of fixing the cables, or with a concentric cable, there is a smaller chance of any person receiving a shock, if the insulation afforded by the conduit is high, or the concentric system is carried out thoroughly; but, in the majority of installations, this is a matter of less importance than the prevention of leakage from one conductor to the other, as this fault may be the cause of a fire, or of an interruption of the service. A further advantage resulting from the use of a system of wiring in which any fault must of necessity be, in the first instance, an earth fault, is that a continuous test may be kept on the insulation whilst the circuit is working; and therefore any falling off in insulation can be known as soon as it occurs; and, as the connection of one conductor to the earth need not interfere with the working of the circuit, there is generally an opportunity of localizing and repairing the fault, before it develops into a short circuit, or in any way necessitates the cutting off of the current.

The periodical testing of installations after they have been put in service is frequently neglected, more especially in the case of internal wiring, because the user does not care to go to the expense of buying a testing set, or of having his installation tested by an electrician. It is, however, possible under certain conditions to make a test with a voltmeter, the testing current being supplied by the dynamo in the case of an isolated installation, or from the supply mains in the case of an installation taking current from a central station. It may also happen that, after a circuit has been put in service, it is inconvenient to cut off the current so as to make a test with a battery and galvanometer; and even if it is possible to test the circuit when the current is off, a test with the

working current is more satisfactory, because it is made under the actual working conditions; and it sometimes happens that a fault may then exist, although the circuit may test well when the current is cut off. For instance, if the working pressure is much higher than that which can be used in conjunction with the testing apparatus, the current may spark across an air gap, or leak over a surface across which the testing current, owing to the smaller strain set up by it, may be unable to pass. Again, it may happen that the expansion of some part of the conducting circuit, due to the higher temperature when the current is on, may cause a fault which disappears again as soon as the temperature falls. The tests which can be made with the working current are not, as a rule, such as will give very accurate quantitative results, and therefore it is advisable to employ both methods; that is to say, an apparatus should be permanently connected in the circuit, which will at all times show whether the insulation is above or below the safe minimum; and at intervals, as an opportunity occurs, the resistance of the cables should be measured by the galvanometer method, so as to obtain a record of the behaviour of the cables themselves.

As the tests that can be made with the working current can be used equally well for testing a complete network of mains or an isolated installation, it is not necessary to deal separately with the testing of house circuits, and we will therefore describe several methods which can be used for either one or the other, first mentioning some methods which, although they do not allow of accurate measurement of the fault resistance, yet give a useful indication of the condition of the circuit. One of these methods, which has often been employed on low-pressure circuits, consists of con-

necting a lamp or lamps to the conductors and to the earth, in such a manner that one will glow when there is a leak of sufficiently low resistance on the circuit. Sometimes two lamps are connected in series between the conductors, and the junction between the two lamps is connected to earth. If the fault resistance of the positive conductor is much lower than that of the negative conductor, the lamp connected to the latter will glow more brightly than the other one; and any change in the brightness of the lamps will therefore indicate a change in the relative values of the fault resistances. If, however, the insulation of both conductors is equally low, the lamps will both glow to the same extent, just as they would if the insulation was good in both cases; and therefore this method is not of much use, except as a handy detector for faults of very low resistance, which seldom occur at the same moment on both sides of the circuit. Another way of employing a lamp as a detector is to connect it up with one terminal to earth, and the other to a two-way switch, by means of which it can be connected first to one, and then to the other conductor. In this case, if the lamp is connected, say, to the positive conductor, it will glow when the added resistances of itself and of the faults in the negative conductor are small enough to allow sufficient current to pass. In both cases, the resistance of the lamp should be as high, and the current required to make it visibly hot as low, as possible; so that an indication may be given of faults which have some appreciable resistance. Of course on low-pressure circuits it is not only the resistance of the mains, but also that of all the installations connected to them, that is measured; and therefore, when a large number of lamps are supplied from a station, one does not have very high

resistances to deal with, and one is content so long as nothing in the shape of a dead earth occurs;—that is to say, a leak of sufficient magnitude to light two or three lamps when connected in parallel between one conductor and the earth is in some cases required, before it is considered necessary to start out on a fault-finding expedition. When this is the case, the simplicity of the lamp method is much in its favour, as the test can be made at any time by the station attendants, who can note when the lamp glows brightly, and report to the electrician accordingly.

A second method is one that has been employed on high-pressure circuits, the apparatus consisting of a vacuum tube placed inside a darkened box, and connected up between the earth and the conductor under test. If the fault resistance is high, there is a visible glow due to the discharge through the tube; but as the fault resistance becomes less, this glow diminishes in brightness, and thus gives an indication of the condition of the mains. A better method than either of the preceding ones is to substitute for the lamps or vacuum tube a recording voltmeter, so as to get a continuous record of the difference of potential between the conductor and earth, and to supplement this, when any great change is registered, by measuring the fault resistance of the circuit by one of the methods which we will now describe.

One of the earliest, if not the earliest published method of accurately measuring the fault resistances of the conductors of a two-wire circuit is one that was described by Dr. John Hopkinson in 1889, in which the dynamo is used to supply current to a Wheatstone bridge, two arms of which are formed of the two fault resistances, whilst the other two consist of a known fixed resistance and an adjustable resistance.

In addition to these resistances, a second resistance coil of known value is required. The connections for this test are shown in Fig. 106, in which + and − are the two main conductors, R_1 and R_2 are the fault resistances of the two conductors from the earth E, R is the known fixed resistance, r the adjustable resistance, and G the galvanometer. To make the test, r is first adjusted until there is no deflection of the galvanometer, when $\frac{R_1}{R_2} = \frac{r}{R}$; then the second resistance coil ρ is connected as a shunt on R_1, and a fresh balance is

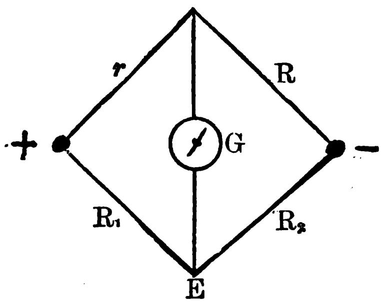

FIG. 106.

obtained say with r_1 ohms in the adjustable resistance, when $\frac{\frac{R_1\rho}{R_1+\rho}}{R_2} = \frac{r_1}{R}$. From these two equations the value of R_1 can be obtained, by substituting in the second equation for R_2 its value in terms of R_1.

Thus $\frac{\frac{R_1\rho}{R_1+\rho}}{\frac{RR_1}{r}} = \frac{r_1}{R}$, and simplifying this, gives $R_1 = \frac{\rho(r-r_1)}{r_1}$.

R_2 can then be found from the equation $R_2 = \frac{RR_1}{r}$.

Several methods of using voltmeters and ammeters for measuring the fault resistance of circuits composed of separate cables, none of which are permanently earthed, without interrupting the service, have been worked out, and the apparatus for making the test by one or other of these methods should be permanently installed in all generating stations. These methods may be divided into two classes, in one of which it is

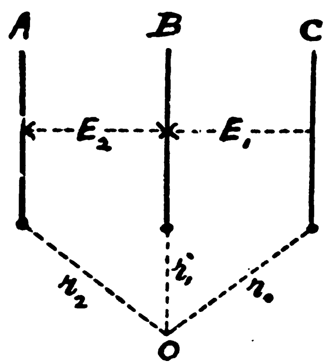

FIG. 107.

necessary to connect two of the conductors in turn to the earth through the measuring instrument, whilst in the other only one conductor is connected to earth, first through the instrument only, and then through the instrument shunted by a known resistance.

METHOD 1. In Fig. 107 let A, B and C be the conductors of a three-wire circuit; r_2, r_1 and r_0 their respective fault resistances, $F = \frac{1}{\frac{1}{r_2} + \frac{1}{r_1} + \frac{1}{r_0}}$ the combined

fault resistance of the circuit, and O the earth taken at zero potential. Let V_2 be the potential of A when it is connected to earth by a voltmeter of resistance G, and V_0 the potential of C when connected to earth by the same voltmeter. We then have

$$\frac{V_2}{r_2}+\frac{V_2}{G}+\frac{V_2-E_2}{r_1}+\frac{V_2-(E_2+E_1)}{r_0}=0;$$

$$\text{or } V_2\left(\frac{1}{F}+\frac{1}{G}\right)-\frac{E_2}{r_1}-\frac{E_2+E_1}{r_0}=0;$$

$$\text{and}\frac{V_0}{r_0}+\frac{V_0}{G}+\frac{V_0+E_1}{r_1}+\frac{V_0+(E_2+E_1)}{r_2}=0;$$

$$\text{or } V_0\left(\frac{1}{F}+\frac{1}{G}\right)+\frac{E_1}{r_1}+\frac{F_2+E_1}{r_2}=0.$$

By subtracting the second from the first we get

$$\left(V_2-V_0\right)\left(\frac{1}{F}+\frac{1}{G}\right)-\frac{E_2+E_1}{F}=0$$

$$\text{whence } F=G\frac{(E_2+E_1)-(V_2-V_0)}{V_2-V_0}=G\left\{\frac{E_2+E_1}{V_2-V_0}-1\right\}$$

We thus see that we can determine the value of the combined fault resistance of the circuit if we know the resistance of the voltmeter and can measure the potential differences between A and C, A and O, and C and O. If instead of E_2+E_1 we put E for the potential difference between the two conductors, which are connected in turn to the earth, we have $F=G\dfrac{E-(V_2-V_0)}{V_2-V_0}$ and this equation may then be used for a two-wire circuit. If a voltmeter which does not indicate the direction of the current through it is used, and the values of V_2 and V_0 are taken without regard to their sign, the sum of the readings must be taken for (V_2-V_0) since the potential of C is necessarily below that of the earth, and V_0 is therefore negative. If an ammeter of resistance G is used in-

stead of a voltmeter $V_2 = A_2G$ and $V_0 = A_0G$, and by substituting these values in the equation given above we get $F = \frac{E - G\,(A_2 - A_0)}{(A_2 - A_0)} = \frac{E}{A_2 - A_0} - G$. Whether an ammeter or voltmeter should be used depends on the value of the fault resistance to be measured, the most accurate results with a voltmeter being obtained when F and G are about equal. For circuits where a fault resistance of 1,000 ohms or more is expected, an ordinary switchboard voltmeter will give good results; but such an instrument would not be suitable for testing an extended network having a fault resistance of only 50 to 100 ohms. In such a case a low-reading ammeter would be better, or the voltmeter may be used with good results if provided with a shunt of about the same resistance as F, the value of G used in the calculation being of course the resistance of the shunted voltmeter.

So far we have only found the value of the combined resistance, but have no information as to the values of the fault resistances of the separate conductors. For a two-wire system these can be obtained directly from the equations given above, as in this case the terms containing r_1 disappear, and we see that $\frac{V_2}{r_2} = -\frac{V_0}{r_0}$, and that the first equation can therefore be written $-\frac{V_0}{r_0} + \frac{V_2}{G} + \frac{V_2 - E}{r_0} = O$,

whence $r_0 = G\frac{E - (V_2 - V_0)}{V_2} = \frac{F\,(V_2 - V_0)}{V_2}$, and in similar manner from the second equation we get $r_2 = G\,\frac{E - (V_2 - V_0)}{-V_0} = \frac{F\,(V_2 - V_0)}{-V_0}$. If an ammeter is used instead of a voltmeter the equations become $r_0 =$

$$\frac{E - G\,(A_2 - A_0)}{A_2} = \frac{F\,(A_2 - A_0)}{A_2} \text{ and } r_2 = \frac{E - G\,(A_2 - A_0)}{-A_0} = \frac{F\,(A_2 - A_0)}{-A_0}.$$

The Board of Trade regulations, as also those published by some of the insurance offices, specify that the leakage current shall not exceed a certain proportion of the maximum supply current, and since the leakage current $C = \dfrac{E}{r_2 + r_0}$ can be determined from the above equations, these voltmeter or ammeter tests will enable us to see if the regulations are complied with.

For a three-wire system the values of the separate fault resistances cannot be determined from the equations given on page 356, as there are only two equations containing three unknown quantities. We can, however, determine the minimum values which any of the three fault resistances can have, as also the maximum possible value of the leakage current, and this information is in most cases sufficient. It is evident from these equations that r_0 and r_2 will have their minimum values when $r_1 = \infty$, so that we get

$$r_2 \text{ min.} = \frac{E_2 + E_1}{-V_0\left(\frac{1}{F} + \frac{1}{G}\right)} = \frac{F\,(V_2 - V_0)}{-V_0} = \frac{F\,(A_2 - A_0)}{-A_0}$$

$$\text{and } r_0 \text{ min.} = \frac{E_2 + E_1}{V_2\left(\frac{1}{F} + \frac{1}{G}\right)} = \frac{F\,(V_2 - V_0)}{V_2} = \frac{F\,(A_2 - A_0)}{A_2}.$$

The maximum leakage current occurs also when r_2 and r_0 have their minimum values, so that we have

$$C \text{ max.} = \frac{E_2 + E_1}{r_2 + r_0} = \frac{-V_2\,V_0\,(E_2 + E_1)}{F\,(V_2 - V_0)^2} = \frac{-A_2\,A_0\,(E_2 + E_1)}{F\,(A_2 - A_0)^2}.$$

The minimum value of r_1 will occur when r_2 or r_0 is

infinite, according to whether V_2 is numerically greater or smaller than V_0. In the former case

$$r_1 \text{ min.} = \frac{E_1}{-V_0\left(\frac{1}{F}+\frac{1}{G}\right)} = \frac{E_1 F (V_2 - V_0)}{-V_0 (E_2 + E_1)} = \frac{E_1 F (A_2 - A_0)}{-A_0 (E_2 + E_1)},$$

and in the latter

$$r_1 \text{ min.} = \frac{E_2}{V_2\left(\frac{1}{F}+\frac{1}{G}\right)} = \frac{E_2 F (V_2 - V_0)}{V_2 (E_2 + E_1)} = \frac{E_2 F (A_2 - A_0)}{A_2 (E_2 + E_1)}.$$

If it is required to find the actual values of r_2, r_1 and r_0 this can be done if it is possible to vary the values of E_2 and E_1, and this change of pressure may be effected occasionally without serious inconvenience to customers if the test is made at the time of smallest output. The method of making the test, which was first suggested to the author by Prof. Rousseau, of Brussels, is first to make the ratio $\frac{E_1}{E_2} = K$ as large as possible, and to measure E_2, E_1, V_2 and V_0 from which the values of K and F can be determined; and then to change the pressures so that $\frac{e_1}{e_2} = k$ is as small as possible, and to measure e_2, e_1 and v_2. We thus get two equations, which can be written

$$\frac{V_2}{E_2}\left(\frac{1}{F}+\frac{1}{G}\right) = \frac{1}{r_1} + \frac{1+K}{r_0} \text{ and } \frac{v_2}{e_2}\left(\frac{1}{F}+\frac{1}{G}\right) = \frac{1}{r_1} + \frac{1+k}{r_0},$$

$$\text{whence } \left(\frac{V_2}{E_2} - \frac{v_2}{e_2}\right)\left(\frac{1}{F}+\frac{1}{G}\right) = \frac{K-k}{r_0}$$

$$\text{or } r_0 = \frac{E_2\, e_2\, (K-k)}{\left(e_2 V_2 - E_2 v_2\right)\left(\frac{1}{F}+\frac{1}{G}\right)}.$$

By substituting this value of r_0 in the first equation,

we can calculate r_1, and when r_0 and r_1 are known, r_2 can be determined by the equation $r_2 = \dfrac{1}{\frac{1}{F} - \frac{1}{r_0} - \frac{1}{r_1}}$.

METHOD 2. Connect any one of the conductors to earth through a voltmeter or ammeter of resistance G, and note the reading V in the former, or A in the latter case; then connect a known resistance S in parallel with the instrument between the conductor and earth, and note the reading V′ or A′. Suppose the conductor A (see Fig. 107) is connected to earth, we have

$\dfrac{V}{G} + \dfrac{V}{r_2} + \dfrac{V - E_2}{r_1} + \dfrac{V - (E_2 + E_1)}{r_0} = 0$, where V is the potential of A when the instrument is joined up between A and earth;

and $\dfrac{V'}{G} + \dfrac{V'}{S} + \dfrac{V'}{r_2} + \dfrac{V' - E_2}{r_1} + \dfrac{V' - (E_2 + E_1)}{r_0} = 0$, when V′ is the potential of A when the resistance S is connected as a shunt on the instrument. From these equations we see that $V\left(\dfrac{1}{F} + \dfrac{1}{G}\right)$ and $V'\left(\dfrac{1}{F} + \dfrac{1}{G} + \dfrac{1}{S}\right)$ are both equal to $\dfrac{E_2}{r_1} + \dfrac{E_2 + E_1}{r_0}$, and therefore

$$(V - V')\left(\frac{1}{F} + \frac{1}{G}\right) - \frac{V'}{S} = 0, \text{ or } \frac{1}{F} = \frac{V'}{S(V - V')} - \frac{1}{G}.$$

Whence $F = \dfrac{GS(V - V')}{GV' - S(V - V')}$, or if an ammeter is used so that $V = AG$ and $V' = A'G$ we have $F = \dfrac{GS(A - A')}{GA' - S(A - A')}$.

If a voltmeter is used, its resistance should be so high that $\dfrac{1}{G}$ is negligible, as in that case the expression

for F becomes $F = \frac{S(V - V')}{V'}$, and the resistance S should be as nearly as possible equal to F to get the best results.

If an ammeter is used, a resistance should be connected in series with the ammeter, so as to get a convenient reading (the value of G being taken as the resistance of the two in series), and S should be made exactly equal to G. The expression $F = \frac{GS(A - A')}{GA' - S(A - A')}$ then becomes $F = \frac{G(A - A')}{2A' - A}$, the best results being obtained when G is equal to or slightly greater than F. The value of G may, however, be made as much as three or four times F without much loss in accuracy, and it is often advisable to settle its value so as to get the readings on the most sensitive part of the scale rather than by its relation to F. Tests by this method are generally made by connecting the middle wire of a three-wire main to earth, but the formulæ hold good whichever conductor is chosen; and if convenient readings cannot be obtained from one of the conductors, the test can be repeated with another. Although the formulæ given above have been obtained for a three-wire system, they hold good for the two-wire and for multiple-wire systems also, as may be seen from the nature of the equations.

For the daily tests which should be made at the generating station, the author has found this voltmeter method the most convenient to use, and would recommend for this purpose the permanent installation of an electrostatic voltmeter, or of a high resistance voltmeter with an even scale, such as the Weston, of three or four resistance coils, which may be used singly or be grouped in parallel so as to allow the

value of S to be varied as circumstances may demand, and of an earth terminal which should be well connected to a thoroughly good earth, so that the resistance of the earth connection is very small.

The values of the fault resistances of the separate conductors can be found by this second method in the same way as by the first, and with the same limitations as regards the three-wire system. For the two-wire system we have $\frac{V}{F} = \frac{E}{r_0}$, whence $r_0 = \frac{ES\,(V - V')}{VV'}$;

and since $\frac{V}{r_2} = \frac{E - V}{r_0}$ we get $r_2 = \frac{ES\,(V - V')}{(E - V)\,V'}$.

For the three-wire system, r_0 and r_2 have their minimum values when $r_1 = \infty$,

so that r_0 min. $= \frac{(E_2 + E_1)\,F}{V} = \frac{(E_2 + E_1)\,(V - V')S}{VV'}$,

and since $\frac{V}{r_2} = \frac{E_2 + E_1 - V}{r_0}$,

$$r_2 \text{ min.} = \frac{(E_2 + E_1)F}{E_2 + E_1 - V} = \frac{(E_2 + E_1)\,(V - V')\,S}{(E_2 + E_1 - V)\,V'}.$$

The maximum leakage current is

$$C \text{ max.} = \frac{E_2 + E_1}{r_2 + r_0} = \frac{(E_2 + E_1 - V)V}{(E_2 + E_1)\,F} = \frac{(E_2 + E_1 - V)\,VV'}{(E_2 + E_1)\,(V - V')S}.$$

The minimum value of r_1 is

$$r_1 \text{ min.} = \frac{E_2 F}{V} = \frac{E_2 S\,(V - V')}{VV'}$$

$$\text{or } r_1 \text{ min.} = \frac{E_1 F}{E_2 + E_1 - V} = \frac{E_1 S\,(V - V')}{(E_2 + E_1 - V)\,V'}.$$

If the values of E_2 and E_1 can be varied, we may as before find the actual value of the fault resistance of each separate conductor, thus $r_0 = \frac{E_2\,e_2\,(K - k)\,F}{e_2 V - E_2\,v}$, from which r_1 and r_2 can be calculated as indicated above.

Although any of the above methods can be used on a direct current low-pressure circuit, when the mains are formed of separate cables and not permanently earthed, certain limitations are imposed as soon as we depart from these conditions. For example, if we have to deal with a similar circuit working with a high instead of a low pressure, the ammeter methods have to be abandoned, and voltmeters and resistances suitable for the higher pressures must be used. Or again, if we change from direct to alternating current, non-inductive instruments and resistances must be employed, and the capacities of the cables, if unequal, will falsify the results. In a two-wire main the normal capacities of the two cables are so nearly equal that the error will not be great, and good results can be obtained with an electrostatic voltmeter and non-inductive resistances. When the capacities are unequal, accurate results cannot be obtained, and one is obliged to rely on the indications afforded by any change in the potential of the conductors, which may be shown by the daily tests.

If concentric mains are used instead of separate cables, none of the above tests are available, since a leakage from the inner conductor cannot get to earth, but passes instead to the outer conductor, forming a more or less complete short-circuit; and unless a special arrangement of pilot wires, to be described further on, is used, one is obliged to rely on the indications given by the blowing of fuses, or by the existence of an excessive drop of pressure. The same difficulty exists in the case of mains in which one of the conductors is permanently connected to earth, so that no method of testing which depends on the difference of potential between the conductors and earth can be used. There is, however, one system of earthing a conductor, which,

as was mentioned in chapter XV., can be arranged so as to permit of periodical tests being made. If the conductor is earthed at one point only and the resistance of the earth connection can be increased at the time of making the test, it is possible to employ method 2 with an ammeter.

Let A, B, E (Fig. 108) be the terminals of a two-way switch, A being connected to one conductor of the mains, and E to earth. Between A and E is con-

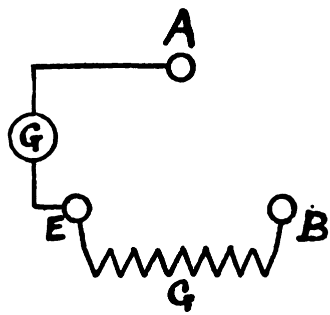

Fig. 108.

nected a low reading ammeter of resistance G, and between B and E a resistance coil equal to G. Under normal working conditions the switch lever is placed so as to connect A and E, thereby putting the conductor A in direct connection with the earth; but when a test is to be made the switch is first opened so that A is put to earth through the ammeter, and then after a reading has been taken it is closed on B, so that A is put to earth through the ammeter, and the resistance coil is parallel. The fault resistance of the circuit can then be found from the formula $F = \frac{G(A - A')}{2A' - A}$, where A and A′ are respectively the

readings of the ammeter unshunted and shunted. The ammeter may be arranged so that it is permanently in circuit between A and E, and the switch connected up so that in its first position it short-circuits a resistance which by opening the switch can be put in series with the ammeter; whilst by putting the switch in its third position on B, a resistance equal to that of the ammeter, plus the added resistance in series with it, is connected in parallel between A and E. This arrangement has the advantage that variations in the readings of the ammeter give indications of the condition of the mains, and if a registering ammeter which at the same time shows the direction of the current be used, a continuous record similar to that obtained with the registering voltmeter is furnished.

The tests that have been described so far only enable us to determine the fault resistance of the complete circuit, including generating machines, interior installations, and all apparatus connected to the mains; and if we wish to measure the fault resistance of any section of the mains or of a house circuit, it is necessary that this section should be disconnected from the rest of the circuit. We can, however, still use a voltmeter as the measuring instrument, and get the testing current from the mains if the test be made by one or other of the following methods, according to whether the resistance of the voltmeter is very great or not.

Let A, B and C (Fig. 109) be the conductors of a three-wire main, and D the terminal to which the conductors of the circuit to be tested are connected after they have been entirely disconnected from the live mains, and let r_2, r_1, r_0 and R be respectively the fault resistances of A, B, C and the circuit under test.

If an electrostatic voltmeter is to be used, A and D are connected by a resistance S, and the difference of potential V between A and O is first measured, and then the difference of potential V′ between A and D; then since $\frac{V}{R+S}=\frac{V'}{S}$, we have $R=\frac{S\,(V-V')}{V'}$.

This formula is only exact when the resistance of

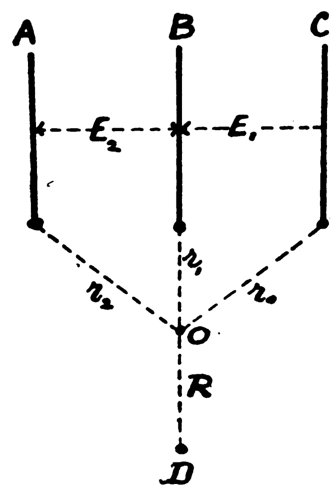

FIG. 109.

the voltmeter is infinity; but it may be used without appreciable error with any voltmeter whose resistance is very high compared with the fault resistance of the mains, so that the difference of potential between A and O is not changed appreciably by connecting the voltmeter between A and O or A and D.

If it is not possible to leave the resistance G of the voltmeter out of account, the test may be made by

connecting the voltmeter in turn between A and O, C and O, A and D, and A and C, and noting the readings V_2, V_0, v and E respectively. If we call v_2 the difference of potential between A and O when the voltmeter is connected between A and D, we have $\frac{v_2}{G+R}=\frac{v}{G}$, and also the following equations—

$$\frac{E_2}{r_1}+\frac{E_2+E_1}{r_0}=V_2\left(\frac{1}{F}+\frac{1}{G}\right)=\frac{V_2(F+G)}{FG}, \text{ and}$$

$$\frac{E_2}{r_1}+\frac{E_2+E_1}{r_0}=v_2\left(\frac{1}{F}+\frac{1}{G+R}\right)$$

$$=\frac{v_2(F+G+R)}{F(G+R)}=\frac{v(F+G+R}{FG},$$

whence $V_2(F+G)=v(F+G+R)$, or $R=\frac{(V_2-v)(F+G)}{v}$,

and since $(F+G)=\frac{GE}{(V_2-V_0)}$, $R=\frac{GE(V_2-v)}{v(V_2-V_0)}$.

Either of these methods may be used for localizing a fault in a house circuit or in a section of the mains, by making the break between the live mains and various portions of the circuit. For instance, if the test of a house circuit made at the main terminals shows the existence of a fault, one may disconnect the sub-circuits at the distribution boards, and repeat the test on the house mains only. If these are good, one remakes the connection at the main terminals, and proceeds to the distribution boards to test between the house mains, which are again under pressure, and each sub-circuit in turn; and by following up this method one can finally localize the fault to any small section, which can be isolated from the rest of the circuit. If the second method is used, it is not necessary to make the complete test each time, as, if the section under test is not faulty, F + G and V_2 remain practically constant, and v is small, so that a sufficient indication

is given by measuring v only, the faulty section being shown by a considerable increase in the value of v.

We have seen that when concentric mains are used, or when one conductor is permanently earthed, none

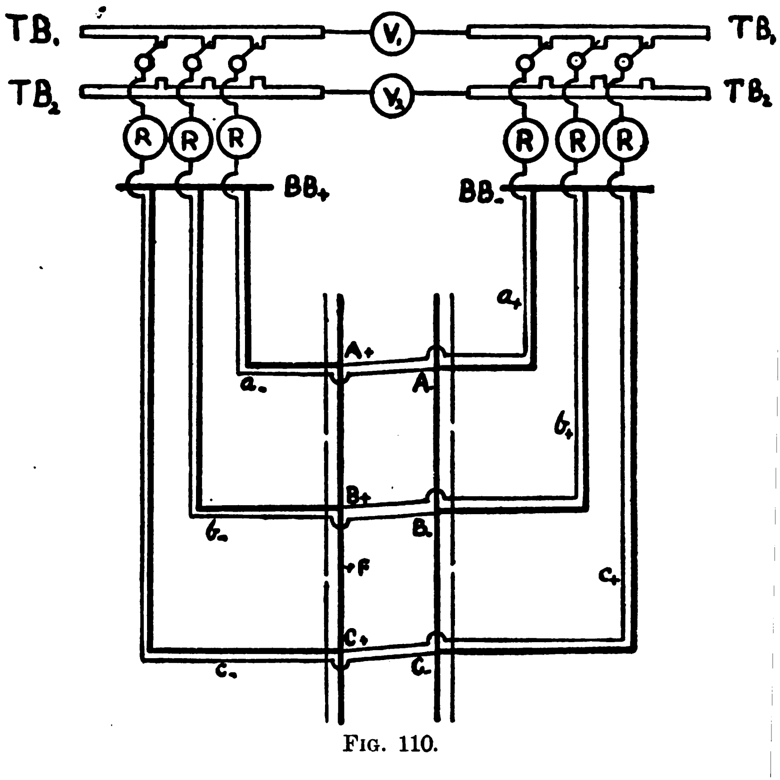

FIG. 110.

of the methods just described depending on measurements of the difference of potential between one or more of the conductors and earth can be used; and we stated that reliance had to be placed on the indications afforded by the blowing of fuses or abnormal drop of

pressure, unless a special arrangement of pilot wires was employed to signal the existence of a fault. Such an arrangement has been worked out, and has been in use for some years on the mains at Berlin, the pilot wires serving the double purpose of connecting the distributing centres to the station voltmeters and of signalling the existence and approximate position of a fault in the network. One of these insulated pilot wires is stranded up with the outside layer of bare copper wires forming the conductor of each cable, the pilot wire in a positive conductor being connected to the negative mains, whilst that in a negative conductor is connected to the positive mains. The connections are shown in Fig. 110, in which A_{+}, B_{+}, C_{+}, ... are the positive terminals of the feeding points, and A_{-}, B_{-}, C_{-}, ... the corresponding negative terminals. These feeding points are connected to the bus bars BB at the station by feeders, and to one another by the distributing mains, as shown by the thick lines in Fig. 110. The pilot wires laid up with the positive conductors are shown by the fine lines marked a_{-}, b_{-}, c_{-}, ... and are connected through fuses to the corresponding negative feeder terminals, a_{-} to A_{-}, b_{-} to B_{-}, and so on. The station end of each pilot wire is connected through a relay R, and a two-way switch to either of two test bars marked TB_1 and TB_2. These relays are so arranged that if more than a certain current passes through one of them it at once opens a switch which breaks the circuit through its coils, and at the same time starts an electric bell ringing. It will be noticed that, although the feeding points A, B, C, ... are connected together by the distributors so as to form one network, the pilot wires are not continuous from one feeding point to another, so that the only connection between the sections *a* and

b, or *b* and *c* is through their respective relays and the test bars.

Under normal working conditions the relays will all be connected by their two-way switches to the test bars TB_1, and the voltmeter V_1 will register the average pressure at the feeding points. If one desires to know the pressure at a particular feeding point, the corresponding switches are switched over on to the test bar TB_2, and the voltmeter V_2 shows the pressure at the feeding point in question. If now a fault occurs, say at the point F, contact is made at that point through the failure of the insulating material between the distributing cable and the pilot b_-, and a short circuit is made from the positive bus bar through the feeder B_+, the faulty distributing cable, the pilot b_-, and the feeder B_-, to the negative bus bar; and the fuse connecting b_- to B_- is blown. The positive cable at F is now connected to the negative mains by a circuit formed of the pilot b_- and its relay coil to the test bar, and from the test bar through all the other relays and pilots in parallel to their corresponding negative feeder terminals. The current in this circuit, the whole of which passes through b_- and its relay, is sufficient to operate this apparatus, but does not affect the other relays, as each of them is only traversed by a fraction of the total current. The relay of b_- then opens its switch and rings the bell, calling the attention of the switchboard attendant to the existence of the fault, and showing that it is in that section of the network containing the pilot *b*.

This system is said to work very satisfactorily in Berlin, but it is evident that it has the disadvantage of signalling the existence of a fault only when this latter has developed sufficiently to burn out the

insulation and to make a contact of very low resistance between the main conductor and the pilot wire. It has, however, the very great advantage of, at the same time, indicating the section of the network in which the fault exists, and of thus diminishing very considerably the labour of localizing the fault if the network is a large one.

The methods of testing which have been described indicate the existence of a fault or measure its resistance; but, with the exception of the pilot wire method last described, none of them give any information as to the position of the fault in the network. The next step is to localize the fault, so that it may be repaired; and this is often a tedious and troublesome operation, as it is of the first importance that such operations should be carried out as much as possible without interrupting the supply of current to any consumer. We may first suppose that the network is mapped out into sections, each around a feeding centre, and we must then find out in which of these sections the fault is situated. The pilot wire method will give us this information, but as, so far as the author is aware, no system of mains exists in England in which the feeder and distributor cables are provided with pilot wires in the necessary manner, other methods must be employed. For low-pressure continuous current networks a first indication can be obtained without actually isolating the sections from one another by means of an induction coil or small transformer connected to a galvanometer. The induction coil may consist of a large number of turns of wire wound on a soft iron ring through which the feeder cable has been threaded, or of a triangular coil, one side of which can be placed against the cable. If a transformer is used, the primary should consist of a

few turns of stout wire capable of carrying the current passing through the feeder at times of light load, when these tests are generally made; and this primary coil should be connected across the feeder switch, so that when this switch is opened, the current must traverse the primary coil on its way to the feeder. The secondary coil must consist of a large number of turns of wire, and must be connected to the galvanometer. If it is known that a fault exists, say on the negative side of the network, the induction-coil round a negative feeder cable is connected to the galvanometer, or the transformer primary is connected in the circuit of a negative feeder, and the positive bus bar is connected to earth through a resistance. The artificial leak resulting from earthing the positive bus bar will cause an increased current to pass through the negative feeders, and the greater part of this extra current will pass through the feeders leading to the feeding centres nearest to the fault. The momentary increase of current in the cable to which the induction-coil or transformer is applied will cause a throw of the galvanometer needle, and this throw will be greater or less in proportion to the amount by which the current in the cable is altered. If, then, the testing apparatus is applied to each of the negative feeders in turn, and the throw of the galvanometer is noted in each case when the positive bus bar is earthed, the feeder which causes the greatest throw is the one which is supplying current to the faulty section. If, as will often be the case, two feeders cause equally large throws of the galvanometer, it will not be possible to say which section contains the fault, but it will then be known that the fault is in a distributor connecting these two feeders together.

This test may only indicate very approximately the

position of the fault, unless it is a very bad one; as the extra current, due to the artificial leak, is divided amongst all the feeders, and the current along any one of them may be too feeble to give a decided throw of the galvanometer needle, especially if the instrument used is not a very sensitive one. Care must also be taken to repeat the test to make sure that the throw of the needle has not been caused by an increase of current due to a customer switching on some lamps, or to other causes beyond the control of the tester. If no sufficiently certain result can be obtained by this test, or if the supply is an alternating current one, in which case this test is not applicable, recourse must generally be had to dividing the network into sections, each of which is isolated from the rest of the network, and is supplied with current by one or more feeders. If the network is divided up in this manner, so that the extra current due to the artificial leak will all pass through the feeder supplying the faulty section, instead of dividing amongst a number of feeders, the above test will give much more decided results, and may be depended on to indicate the section in which the fault exists unless its resistance is very high compared with the aggregate fault resistance of the network.

Another method, which can be used if the network is divided up into sections, is to temporarily transfer each section on to a spare bus bar and feed it from a separate generator, so that the fault resistance of each section in turn can be measured by the voltmeter or ammeter methods described in the earlier part of this chapter. This method is applicable to both continuous and alternating current circuits where special disconnecting boxes have been provided in the network. When low-pressure distribution from transformer sub-

stations is employed, and all the transformers feed into a common network, the high-pressure feeders can be disconnected one by one during the time of light load, and can be tested separately; and afterwards the low-pressure network can be divided into sections, and each section can be tested from the sub-station which supplies it with current. When each sub-station supplies its own independent network, the feeders cannot be disconnected without interrupting the supply, and they must therefore be switched on to a special alternator as described above. If, as is often the case, the network is fed from two or more generating stations, or from a generating station and a battery sub-station, and disconnecting boxes have been provided, a convenient method of testing is to temporarily divide the network into two parts, one fed from each station, and to test each for fault resistance. By transferring sections of the network from one part to the other, and testing, by the voltmeter method, after each change of grouping, the section containing the fault can be discovered.

A method, also requiring provision for disconnecting sections of the network, has been described by Mr. Quin, in a paper read before the Municipal Electrical Association, in which a differential ammeter is inserted in the main, which, during the test, forms the feeder from the network to the isolated section. The instrument is an ammeter wound with three coils, one of which is inserted in the circuit of each cable of the three-wire main, in such a manner that all the current going to or returning from the section under test must pass through it. When the ammeter is connected up, either in a feeder circuit at the station, or in circuit with any main leaving a disconnecting box, a section is isolated so that its only connection with the rest of

the network is through the ammeter, and an earth connection is made with the mains on the station side of the instrument. If there is no fault in the isolated section, the algebraic sum of the three currents passing through the instrument is zero, and the ammeter needle is not deflected; but if there is a fault, say, in the negative cable of the isolated section, a circuit is completed from this cable to earth, and through the earth connection to the positive cable on the station side of the instrument, and this leakage current flowing through the negative coil of the ammeter destroys the balance of the three coils and deflects the needle. The ammeter must be arranged so that its coils can carry large currents without injury, whilst at the same time it must be very sensitive, so as to be able to give a deflection with a very small leakage current; and as these conditions are not easily attained, the author prefers for continuous current circuits the method already described of inserting a transformer, the secondary coil of which is connected to a galvanometer, in one main, whilst making intermittent earth with the other.

The various methods described above, although not so sensitive as the voltmeter methods mentioned on page 367, all have the advantage that they can be applied without interrupting the supply of current to any part of the network, and a preference should therefore be given to them, owing to the immense importance of maintaining continuity of supply. When the fault has been localized, as nearly as it is possible, by one of these methods—that is, when one has found that the fault is in a feeder, or in a certain length of distributor between two disconnecting boxes—there still remains the localizing of the actual position of the fault in the length of cable, and this last step is

often the most difficult task of all. For a fault in a feeder, the author has found that the loop test is generally practicable, as a high voltage battery and instruments permanently set up in the station testing-room can be used. It is advisable to use four test wires, one from each end of the loop to the galvanometer, and one from each end of the loop to the bridge resistance; as it is easier to correct for the resistance of these test wires in the galvanometer and bridge circuits than it is if they form part of the loop under test. If the fault is in the distributing network, the loop test is seldom practicable, owing to the low conductor resistance of the loop, and the difficulty of using a high battery power and sufficiently sensitive instruments in the streets, where all the apparatus must be portable. If the system is a drawing-in system, the fault may be localized near enough to determine that it is somewhere between two surface-boxes, and the length of cable may then be drawn out and replaced; but if there are many services taken off the cable, or if the cable is laid on the built-in system, this is no longer practicable, and a more exact localization is required than is possible by the loop test.

It is then necessary to resort to methods which do not depend on the measurement of a resistance, such as the telephone and induction coil method, or the compass test. For the former test, a coil of many turns, wound on a rectangular frame four or five feet long by about the same height, is connected to a telephone, and is carried along the streets immediately above the cable to be tested, whilst an alternating or intermittent current is sent through this latter to earth. This alternating current induces a current in the coil and causes the telephone to hum, and the tester listening at the telephone, as the coil is carried along, can tell

when the fault is passed by the cessation of the sound. The idea is an ingenious one, and the apparatus has been used with success in various places; but on the other hand, many people who have tried this method have been unable to obtain any satisfactory results. This want of success is due to the fact of the cables being surrounded by a metallic sheathing or laid in iron pipes, or to the presence in the ground of water and gas pipes, which may serve as a good return conductor for the earth current, and be in such a position that the inductive effect of the current in them may nearly neutralize that of the current in the cable under test.

The compass test is made by placing a compass over the cable to be tested, and after bringing the needle parallel with the cable by means of a small directing-magnet, sending a current through the cable to earth. If there are no other disturbing forces, the compass will always be deflected so long as it is on the near side of the fault; but as soon as the fault is passed, there is no longer a current flowing in the cable, and the compass is not deflected. This test is open to the same objections as the telephone test described above, and further, it requires a very considerable current to be sent to earth; and if there are other cables in the same trench it is necessary to cut the current off them, so that they may not influence the movement of the compass.

Another method depending on the telephone has been described by Mr. Quin, in a paper read before the Municipal Electrical Association, in which the position of the fault is detected, not by the cessation of sound from the telephone, but by a change in the tone. At each end of the length of faulty cable a connection is made to earth through the secondary

of an induction coil, the primary of which is excited either by current from the mains or from a separate battery. The contact breakers of the two induction coils are of different lengths, and are arranged to give frequencies which will produce two easily distinguishable notes in the telephone. From one end of the cable to the fault there is then a current of one frequency, whilst from the other end of the cable to the fault there is a current of a different frequency, so that as the search-coil with its telephone is carried along over the line of the cable, the listener, as he passes the fault, hears a change in the note given by the telephone. Mr. Quin has used frequencies of 84 and 160, which produce notes nearly an octave apart, and states that with his search-coil and telephone a current of one ampere gives a distinctly audible hum at a distance of 10 feet.

The several methods of locating the exact position of a fault which have just been described, all require that the faulty length of cable shall be disconnected from the network, and consequently the supply must be cut off from a certain number of consumers during the time that the test is being made. It is, therefore, of great importance to arrange that the network can easily be divided up into small sections, so as to inconvenience as few consumers as possible, and that every part of the network can be supplied with current by at least two alternative routes, so that no consumers, except those actually connected to the cable under test, need have their supply interfered with.

APPENDIX.

NOTE A.

A committee, consisting of representatives from the Institution of Electrical Engineers, the Post Office, and a number of firms manufacturing insulated cables, held several meetings in 1899 to fix a specification for copper conductors which should be commonly adopted by them. The report of this committee (copies of which were published in the *Journal of the Institution of Electrical Engineers* [No. 142] and in the technical journals) gives the following standards as those adopted for annealed high conductivity commercial copper.

The resistance of a wire one metre long weighing one gramme is ·150822 standard ohms at 60° Fahr. The weight of a cubic foot of copper at 60° Fahr. is 555 lbs. The temperature coefficient is 0·00238 per degree Fahrenheit.

These figures give a specific gravity of 8·912, which practically agrees with the figure used by the author, and a resistance per mil. foot of 10·2044 ohms at 60° Fahr.

If these figures be adopted, together with the temperature coefficient named above, the figures given in Table II. (pages 20 and 21) would be correct for wires having 98½ per cent. conductivity.

NOTE B.

It has been pointed out that the data for fixing accurately the cost of upkeep of mains and the percentage to be allowed for depreciation are still very incomplete. Firstly, there are but few systems of mains which have been in use for ten years or more; and even with those that date back thus far, a large proportion of the present capital expenditure represents cables laid in the last two or three years, as in every case there is a continual extension of the distributing system each year. Again, in the majority of cases two or more types of mains are in use, and the accounts of the companies and municipalities supplying electricity do not, of course, state the cost of upkeep separately for each type. A further difficulty arises from the fact that in some accounts separate figures for wages and renewals are not given, but the amounts for these and other items of expenditure are given in one lump sum.

As, however, it may be found useful to have such figures as are obtainable presented in tabular form, the author has prepared the table below, in which are given for various undertakings the types of mains in use, the capital expenditure, and the cost of distribution wages and renewals. In preparing

this table, the figures given in the analyses of the accounts of supply undertakings published from week to week in *The Electrician* have been used, but the amounts given below as spent on wages and renewals are in each case half the sum of the last two years' expenditure, and the figures given under the heading of capital are the amounts expended up to the end of the earlier of these two years, *i.e.* up to the middle of the period for which the average cost of upkeep is given.

No undertakings are included which had not commenced supply in 1894 or earlier, as the figures for the first two or three years' working are often very misleading, owing to the existence of maintenance clauses in the contracts made with the contractors for the cables; nor are any figures given for undertakings where the capital expenditure is less than £10,000.

	Capital Expenditure.	Distribution.			Type of Mains.
		Wages.	Renewals.	Total.	
1882.	£	£	£	£	
Eastbourne . .	14,020	246	217	463	Rubber, diatrine.
1887.					
Kensington and Knightsbridge	85,733	775	1,587	2,362	Bare copper, rubber.
1889.					
Bath	12,533	not given	separately.	78	Bitite.
Bradford . . .	73,157	279	284	563	Lead-covered jute and paper.
Chelsea . . .	87,375	904	747	1,651	Bitite.
House to House	64,556	286	82	368	Paper, rubber.
St. James' and Pall Mall . .	69,557	not given	2,050	2,050	Bare copper, jute, bitite, paper, rubber.
1890.					
Charing Cross .	123,089	984	1,761	2,745	Bitite, jute.
Metropolitan Co.	295,310	not given	separately.	2,161	Rubber, paper.
Newcastle District	18,417	553	nil	553	Rubber.
Westminster .	233,609	1,616	1,113	2,729	Bare copper, jute, rubber.
1891.					
Birmingham .	103,045	not given	separately.	742	Bare copper, bitite.
Bournemouth .	27,998	237	86	323	Rubber, jute.
Brighton . . .	102,499	742	941	1,683	Lead-covered jute.
City of London	405,038	4,663	3,998	8,661	Paper, bitite, rubber.
Notting Hill .	69,984	not given	separately.	123	Bare copper.
St. Pancras . .	107,448	,, ,,	,,	3,285	Bare copper, jute, rubber.

	Capital Expenditure.	Distribution.			Type of Mains.
		Wages.	Renewals.	Total.	
1892.	£	£	£	£	
Cambridge . .	15,205	65	nil	65	Rubber, paper.
Glasgow . . .	82,965	not given	separately.	2,596	Bare copper, jute, paper, rubber.
Oxford. . . .	33,930	186	73	259	Rubber, bitite.
Preston . . .	31,739	not given	separately.	165	Bare copper.
1893.					
Blackpool . .	22,365	not given	separately.	437	Paper.
Bristol . . .	45,946	285	347	632	Jute, paper.
Derby	25,321	54	168	222	Jute, paper, rubber.
Dundee . . .	13,904	not given	separately.	60	Bare copper, rubber.
Huddersfield .	27,262	73	299	372	Rubber, paper, bitumen.
Hull	28,934	132	417	549	Bare copper, rubber, bitite, jute.
Manchester . .	157,129	864	1,783	2,647	Bare copper, rubber, bitite.
Richmond . .	20,221	51	30	81	Bare copper, rubber.
Scarborough .	11,171	109	97	206	Rubber.
Sheffield . . .	40,880	not given	separately.	359	Paper, rubber.
1894.					
Aberdeen. . .	16,242	nil	182	182	Bare copper, jute, paper, bitite.
Bedford . . .	21,654	78	26	104	Rubber.
Bolton	16,943	2	45	47	Rubber, paper, jute.
Burton . . .	14,355	nil	57	57	Rubber.
Cardiff. . . .	19,990	68	184	252	Rubber, paper.
Halifax . . .	16,083	57	30	87	Rubber.
Hampstead . .	49,008	not given	separately.	157	Jute, diatrine, paper.
Hanley . . .	16,606	61	288	349	Paper, bitite.
Lancaster . .	10,142	10	40	50	Bitite.
Leicester . . .	17,814	266	162	428	Jute, paper.
Nottingham .	23,894	57	59	116	Bitite.
Portsmouth. .	44,391	not given	separately.	632	Rubber, paper.
Southport . .	20,325	87	139	226	Jute, paper.

The total capital expenditure on mains for the 44 undertakings named above is £2,737,787, and the total cost of wages and renewals as given above is £41,877, or an average of 1·53 per cent.

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